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Novel Technology for Utilization of Solid Organic Waste in Recultivation of Abandoned Mining Areas

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for doctoral or equivalent academic degree.

Jüri Järvis

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signature

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Tehnoloogia väljatöötamine tahkete orgaaniliste jäätmete kasutamiseks endiste kaevandusalade rekultiveerimisel

JÜRI JÄRVIS

TTÜ KIRJASTUS

I dedicate the work to mother Earth.

We, humans, inhabit an ecosystem called Earth. Similarly to all the systems we use, we have to take care of them, maintain and fix them in order to use them longer. This work tested some methods for fixing our commonly shared ecosystem on planet Earth.

Contents

List of publications

This doctoral thesis is based on four publications in international peer-reviewed journals that are indexed by the ISI Web of Science or Scopus. The publications are referred to as Paper I−Paper IV in the text. The four publications are as follows:

Paper I: Jüri Järvis; Mari Ivask; Lembit Nei (2012), Artificial rope-wick roots improve the germination and establishment of tree species. Seed Science and Technology, 40 (3), 433−436

Paper II: Jüri Järvis; Mari Ivask; Lembit Nei; Annely Kuu; Aarne Luud (2016), Effect of green waste compost application on afforestation success. Baltic Forestry, 22 (1), 90−97

Paper III: Egge Haiba; Lembit Nei; Mari Ivask; Jane Peda; **Jüri Järvis**; Merike Lillenberg; Karin Kipper; Koit Herodes (2016), Sewage sludge composting and fate of pharmaceutical residues – recent studies in Estonia. Agronomy Research, 14 (5), 1583−1600

Paper IV: Jüri Järvis; Mari Ivask; Lembit Nei; Annely Kuu; Egge Haiba (2017), Afforestation of cutover peatland with spot application of sewage sludge compost. Baltic Forestry, 23 (3), 644−657

Author’s contribution to the publications

Paper	Original idea	Study design and methods	Data collection and analysis	Contribution to interpretation of results and manuscript preparation	Responsible for interpretation of results and manuscript preparation
I	JJ	JJ	JJ	JJ, MI, LN, AK, EH	JJ
II	JJ	JJ	JJ	JJ, MI, LN, AL	JJ
III	LN, EH	LN, EH	LN, EH	EH, LN, MI, JP, JJ, ML, KK, KH	EH, LN
IV	JJ	JJ	JJ	JJ, MI, LN	JJ

AK – Annely Kuu; AL – Aarne Luud; EH – Egge Haiba; JJ – Jüri Järvis; JP – Jane Peda; KH – Koit Herodes; KK – Karin Kipper; LN – Lembit Nei; MI – Mari Ivask; ML – Merike Lillenberg

Introduction

Damaged environment is a global problem. Environmental concerns related to mining activities are evident and usually more intense in the case of abandoned mines and reflect the difficulties involved in their rehabilitation. Globally, large areas of abandoned mining areas require reclamation (Dutta et al., 2016). These lands are often characterized by high acidity, depleted levels of soil organic matter and nutrients such as nitrogen and phosphorus, and with high erodibility (Milder et al., 2013; Raizada & Juyal, 2013; Chaudhuri et al., 2015; Haigh et al., 2015). Mining results in the enhanced soil erosion, mineralization and leaching (Lal et al., 1998). As a rule, these degraded conditions result in deposition of eroded sediments in nearby waterways (Bendfeldt et al., 2001). According to Earth's Crust Act (Earth's… 2016), one option for reclamation of depleted opencast mining areas is to render the land to its former purpose. That means the area must be recultivated to bring the land back into the state where preconditions are created for self-sufficient ecosystem to emerge and produce biomass again. The easiest way to start an ecosystem on degraded land is to create plant cover on it, for example by planting trees. All the missing plant nutrients must be applied to the soil in order to enable plants to grow on nutrient-deficient soils. Also, water availability must be ensured to enable plants to use required nutrients.

One possibility for increasing the amount of nutrients in the soils of depleted mines is to apply nutrient-rich waste. Land application of biosolids is generally considered to be the best option of their usage because it offers the possibility of recycling nutrients (Haiba et al., 2016). These waste materials contain all the macro- and microelements that plants need, but include also contaminants that may cause problems when the waste is used in agriculture. The city-derived waste materials of interest are sewage sludge and waste from city greenery (tree leaves, grass clippings etc.).

The need to utilize sewage sludge from cities wastewater treatment plants (WWTP-s) is apparent and its usage on "corrupted" areas could partly help to solve this problem. Sewage sludge contains high amounts of plant macronutrients such as nitrogen, phosphorus, potassium, calcium, magnesium and wide assortment of micronutrients. High organic matter content in sewage sludge makes it a potentially very promising source for improving soil quality (White et al., 2011). Sewage sludge application in abandoned opencast mining areas improves the soil fertility and alleviates waste disposal problem, which may be an inexpensive and effective alternative to the methods applied currently as for example mineral fertilization or manure disposal (Oleszczuk et al., 2012). Unfortunately, the use of sewage sludge is limited due to the presence of a number of pollutants in it, as for example pharmaceutical residues. Sewage sludge contains over 60,000 toxic substances and chemical compounds, especially heavy metals and harmful organic pollutants (Li et al., 2014).

To overcome this drawback, composting of sewage sludge is often used to reduce the quantity of harmful microbes (pathogens) and to decompose chemical contaminants (including pharmaceutical residues). However, some pharmaceuticals do not decompose fully during composting (Narumiya et al., 2010, Reichel et al., 2013, Haiba et al., 2016). By using the sewage sludge compost for food crops, plants may take up chemical contaminants from compost (Kipper et al. 2010) and the surfaces of plants may become contaminated by the microbes present in the compost. In the case when sewage sludge compost is spread evenly on the recultivated mining areas to create fertile organic layer to support a plant cover growth over the area, there is a strong threat that the contaminants leach into groundwater. Pharmaceutical residues, for example antibiotics, reach plants directly or through groundwater and can cause resistance against the antibiotics when consumed (Torri et al., 2012). Currently there are no existing trigger values in the European Union for drug residues in compost and in soil (EU Council Directive 86/278/EEC). The document that sets limits for the drug residues which are allowed to reach soils is the act that regulates their content in manure (EMEA/CVMP/055/96). According to this act the content of drug residues in manure are limited to 100 µg kg^{-1} and 10 µg kg^{-1} in the soil that is fertilized with manure. In a study carried out by Monforts (2005) the recommended drug residues limit has been set to 1 µg kg^{-1} in soil.

Urban green compost, which has been produced by composting tree leaves and grass clippings from densely populated city environments, may contain excessive amounts of chemical contaminants, as for example heavy metal substances, polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs), from polluted air. The possible risks caused by contaminants present in urban green compost are evident (El-Nagerabi et al. 2012, Gliniak et al. 2017). For this reason its usage for cultivating food crops cannot be suggested.

There is no doubt that for the reclamation of abandoned mining areas their surface layer needs to be fertilized. The use of both sewage sludge and urban green composts can be a risk for the environment and human health. The aim of the current study was to find the ways of minimizing this undesirable side-effects that might accompany the measures undertaken in abandoned mining areas rehabilitation, and to develop an environmentally sound and economically acceptable methodology for afforestation of these lands.

Environmental security is a major challenge in the rehabilitation of abandoned mining areas. The current study has been compiled with the aim to develop a novel technology that is environmentally more secure and applicable in recultivation and provides seedlings with needed nutrients and water in their initial phase of growth after planting in comparison with the existing practice. During the work a new method for using sewage sludge compost and green compost derived from city greenery was developed and tested. The method was planned to be applicable in recultivation and regeneration of some abandoned mining area types like cutover peatlands. It was taken into consideration that the utilization of the method should meet the limits set by legal acts for disseminating nutrients, heavy metals and pharmaceutical residues into soil.

1 Literature review

1.1 Abandoned mining areas and their recultivation

Recultivation is an eficient way of restoring biodiversity (Kikamägi et al. 2013). Afforestation of the abandoned mining areas as a form of recultivation has been considered a sustainable and promising recovery option due to subsequent wood production. Degraded peatlands that cover 0.3% of the global land area are responsible for disproportionately high amount, 5% of global anthropogenic CO_2 emissions (Joosten 2009). When looking for a method for reducing greenhouse gas emissions, recultivation of cutover peatland by trees for timber production could have a reducing effect.

Draining cutover peatland is often needed as a prerequisite for afforestation because planted trees need an aerobic layer in soil for their roots to survive. After draining, the decomposition process of peat speeds up, offloading greenhouse gas carbon dioxide (CO_2) into atmosphere (Byrne and Farrell 1997, 2000, Waddington et al. 2002). However, trees sequester CO_2 and store it in timber. The studied afforested peatlands in Scotland have shown accumulating more carbon into timber, forest litter and soil than releasing it into atmosphere (Hargreaves et al. 2003). Furthermore, rewetting cutover peatlands and revegetation with mosses has also been found to reduce the greenhouse gases nitrogen dioxide (NO_2), CO_2 and methane (CH_4) significantly (Järveoja et al. 2016). The carbon balance of bare (burned) peatland can be remarkably improved by revegetating bare peat with the help of seeding natural vegetation, liming and fertilizing (Worrall et al. 2011). The need for recultivation of abandoned cutover peatlands was found to be around 7,000 hectares in Estonia. In general, revegetation coverage on the abandoned peat mining areas was estimated to be around 20% (Orru et al. 2016). Altogether, in three Baltic States, abandoned cutover peatlands area exceeds 26,000 ha (Karofeld et al. 2017).

The environmental impacts from planting and cultivating trees on abandoned sand and gravel quarries are predominantly positive. Trees assist to reduce greenhouse gas by sequestering CO_2 from the atmosphere, and they simultaneously produce timber, reduce erosion and create new ecosystem (Buttleman 1992, Ehitusmaavarade 2017). For example, 43% cases of sand and gravel quarries are assigned for regeneration with planting trees after depletion in Estonia (Keerberg 2015).

A good example of successful recultivation using afforestation can be seen at the Estonian Northeastern depleted oil-shale mining areas. Most of the exhausted oil-shale mine areas have been reforested. Still, there are difficulties in promoting soil formation process on these very stony areas where the contents of nitrogen and organic matter in the mining spoil are low. Therefore, it was suggested (Lõhmus et al. 2006) to plant black alder (Alnus glutinosa) as a nitrogen-fixing tree species. This species receives nitrogen from air through its root nodules and synthesizes it into plant available form. Another soil formation promoting property of black alder is the ability to extract phosphorus from rocks into plant available form through its roots activity (Giardina et al. 1995). The use of specific tree species is a mean of fertilizing the "corrupted" areas through the plant activity. The selection of the right tree species enables accelerating ecological restoration processes through speeding up soil formation processes (Lõhmus et al. 2006; 2007).

The methods for recultivation tested on nutrient-deficient peat soils without adding nutrients have given poor growth results (Pearson et al. 2011). Supporting tree seedlings growth during the first years of development when recultivating oil shale mining areas has been considered critical for tree survival (Lõhmus et al. 2007), and the quality of soil has been shown to be of utmost importance (Vaus 1970). The recultivation of abandoned mining areas with nutrient-poor soils has been supported with mineral fertilizers under conditions where soil aeration and water availability were sufficient (Raid 1979, 1986, Valk 1992, Pikk 2001, Renou and Farell 2005, Renou et al. 2007). The examples of successful support for recultivation of cutover peatlands with other waste substances, like wood ash or peat ash, have been published by Huotari et al. (2008), Pärn et al. (2009), Kikamägi et al. (2013) and Hytönen (2016). The mixture of oil-shale ash and wood ash for fertilizing cutover peatlands for cultivating silver birch and Scots pine seedlings has also shown positive results (Ots et al. 2017).

There is also a need to improve water availability in mining areas during the time of temporary water deficit. Hydrogels are applied during planting to soil or to seedlings roots to store rainwater and keep it available for the roots (Sarvaš 2007). Hydrogels are hydrophilic polymers that absorb and store large amounts of water. In a recultivation test on sandy loam soil, hydrogel-filled drilled holes significantly supported seed germination compared to reference seeding (21.8% and 16.2% respectively) (Pamuk 2004). The artificial roots created by G.S. Pamuk from hydrogel powder have resulted in better seeds germination in water-deficient soils. It is important to support recultivation by increasing water and nutrient availability to the recultivated seedlings; therefore, mechanical planting machines are supplied with water-hydrogel and fertilizer applying devices (Bracke, M-planter, Risutec 2017).

The concentration of water in porous substance such as soil or rope-wick can be sufficient for germinating seeds, being in the form of vapor (Wuest 2002, 2003, 2007). Therefore it is not always necessary to provide liquid water-seed contact. To get precise but easily achievable results for the quantity of water *Q* taken into the germinating seed during any given time span *t* during germination time, the differences of seed volumes can be used based on the seed volume change. The volume of seed V_{0t} at the beginning of the time period and the volume of the seed V_{ft} (f-for final) at the end of the time period can be used in calculations:

$$Q_t = V_{ft} - V_{0t}$$

A number of different methods have been developed to enhance the conditions of seedling growth. Growing seedlings for recultivation in deep and voluminous containers with high nutrient content (especially phosphorus) and properly chosen well irrigated growth substrate (peat, vermiculite and perlite for example) enables fast growth of seedlings in nursery. However, lower growth rates were obtained with pine bark based growth substrate (Derby and Hinesley 2005). Bigger seedlings have higher potential for further growth when planted into fertile substrate on a regenerated area. Recultivation from seeds by maintaining high moisture levels around seeds during germination has been tested with soil covering disks made of paper, polymer and vermiculite. Preliminary test results have shown positive germination rate tendencies compared to reference seeds sown on ground (Winsa 2016). Recultivation with pressed peat pucks containing seeds has been tested for the same reason (Landström 2017). The test was arguably successful but has no scientific proof. Growth supporting rainwater collecting and accumulating container-structures introduced under the trademark “Groasis” have been used for recultivation purposes in relatively dry climate zones (Groasis 2017).

1.2 Anthropogenic waste in recultivation

There are several studies about the usage of anthropogenic waste in recultivation processes. For example, oil-shale ash mixed with phosphorus-enriched filter-peat from a wastewater treatment plant (WWT) has been used. The authors showed promising results in the case of silver birch seedlings for recultivation purposes (Kõiv et al. 2012). The recultivation of cutover peatland with application of sewage sludge, which was surface-spread and mixed with upper soil layer, has resulted in high gains in the height growth of tree seedlings (Pikka 2005, 2006, Pikka et al. 2013). However, the usage of surface-spread sludge has showed high weed competition for light, which decreased the survival of seedlings (Lazdiņa et al. 2013) and required monthly weeding (Pikka 2005). In a study carried out by Harrison et al. (1994), the excess usage of sewage sludge for soil amendment resulted in a negative effect on tree growth through nitrification process, acidification of soil and leaching out cations that lead to the shortage of magnesium in soil. Additions of compost in planting holes to improve plant growth were a common efficient practice in planting greenery (Caubel et al. 2010).

Besides sewage sludge treatment product (biosolid) another biosolid material, biochar has shown to improve tree seedlings growth (Scharenbroch 2013), while improving chemical, physical and hydrological characteristics of fine sand and sandy loamy silt soils (Ajayi and Horn 2016). Biochar (charred organic material like wood, straw etc.) is a promising substance in the amendment of nutrient-deficient soils. Biochar amendment increases nutrient content in soil and also improves soil's water regime by storing water in its particles (Ortaş 2016, Page-Dumroese et al. 2016, Zhang et al. 2016). Hence, biochar is a possible substance which can be used on abandoned mining areas for recultivation in the future.

Composting is one of the sustainable ways of recycling organic wastes. The nutrient rich compost is not always suitable for increasing soil fertility due to possible biological and/or chemical contaminants in the compost. By using the sewage sludge compost for food crops, the plants may take up chemical contaminants like fluoroquinolones and sulfonamides from compost (Kipper et al. 2010) and the surfaces of the plants may become contaminated by the microbes found in the sewage compost. Therefore, the application of high quantities of such compost by spreading it evenly on the ground for recultivation purposes cannot be suggested. It causes higher risk of target soil contamination through higher amounts of compost is needed to fertilize a hectare. According to Nilsson and Lundin (1996), Lehmann and Stroth (2003), Shoumans (2015), usage of urban-derived composts can only take place with certain restrictions to avoid or minimize the leaching of contaminants and nutrients into groundwater.

1.3 Contaminants in sewage sludge compost

There are clear environmental concerns in using urban biosolid wastes. Despite the nutrients present in sewage sludge and its compost, they also contain a number of toxic pollutants (Lillenberg et al. 2010, Lillenberg 2011, Haiba et al. 2016). Approximately 4,000 pharmaceutical substances are used in Europe, both in human and veterinary medicine. Medicaments such as analgesics, antibiotics, anti-inflammatories, antidepressants and antiepileptic drugs do not decompose completely in human body (Zhang et al. 2008, Vasskog et al. 2009, Bergersen et al. 2012) and end up in sewage sludge. A number of studies have shown that pharmaceuticals reach the environment mainly through sewage sludge and its compost (Nouri et al. 2008, Jelic et al. 2011, Kim et al. 2012, Rodriguez-Rodrigues et al. 2012, Borgman and Chefetz 2013, Reichel et al. 2013, Haiba et al. 2016, Kipper et al. 2017). Pharmaceuticals in general can reduce the microbial-mediated processes like the regeneration of nutrients by microbial vital activity, circulation of carbon and nitrogen, also digestion of pollutants in soil (Girardi et al. 2011, Jelic et al. 2011, Bergersen et al. 2012, Chen et al. 2013, Li et al. 2014, Haiba et al. 2016).

Pharmaceuticals are present in soil and groundwater (Mompelat et al. 2009, Rodriguez-Rodrigues et al. 2011). About 150 pharmaceutical compounds are found in the environment, mostly in water samples (Rivera-Utrilla et al. 2013, Li et al. 2014). Individual concentration of a drug can be low but the combined concentration of drugs that have the same mechanism of action could be remarkable (Daughton and Ternes 1999, Haiba and Nei 2017). Undesired impacts may appear when there is periodical and continuous contamination of soil environment with pharmaceutically-active substances (Barbosa et al 2016, Verlicchi and Zambello 2016). Furthermore, bioaccumulation may reach toxic concentrations through food chain (Straub 2016, Haiba and Nei 2017). Soils in arable lands and pastures containing antibiotics and other pharmaceutical residues can transmit the substances to plants and cause drug resistance in consuming organisms (Davies 1994, Haiba and Nei 2017). It is assumed that the drug residues that reach the soils through fertilizing the soils with manure or sewage sludge is one of the main reasons that increase drug resistance (Knapp et al. 2010, Haiba and Nei 2017). Genes that determine drug resistance can be transferred from harmless soil microbes to pathogenic microbes (Davies 1994, Haiba and Nei 2017). One of the factors which likely promote micropollutants degradation during composting is the presence of fungi in the composted matter (Zhang et al. 2011). However, more research is needed on that topic to confirm the results in the scarce literature sources (Butkovskyi et al 2016, Haiba et al. 2017).

Some studies describe experiments that were made to seek for the best bulking agents for composting sewage sludge to degrade the pharmaceutical residues in the shortest time. Simultaneously, for successful recultivation, the bulking agents must fit to foster seedlings roots growth. For example, fine-textured hardwood sawdust has helped to degrade pharmaceuticals the fastest (Ammari et al. 2012, Kim et al 2012, Nei et al. 2015, Haiba et al. 2016). In a study by Lillenberg (2011), peat as a bulking agent enhanced degradation of pharmaceutical residues from anaerobically digested sewage sludge faster than tree bark which was used in another study where raw sewage sludge was composted with bark shavings (Haiba et al. 2016). This is probably due to the larger surface area of fine sawdust and better availability to microbial processes. It is important to note here that the tree seedlings grow faster in peat-dominating substrate than in a substrate made mainly from tree bark (Derby and Hinesley 2005).

1.4 Contaminants in city-derived green compost

An important gasoline-derived contaminant group is polyaromatic hydrocarbons (PAHs). PAHs are derived from incomplete combustion of fossil fuels, also from burning garbage, from asphalt and coal tar (Lee and Vu 2010, Kuppusamy et al. 2017). Concentrations of 23 PAHs in 20 New York City (USA) community gardens soils was studied and high variation of concentrations of PAHs were found suggesting a consistent relationship between historical deposition of atmospheric carbon-adsorbed PAHs and current PAH soil concentrations (Marquez-Bravo 2015).

One of the most common contaminants which can be found in urban green compost is lead, from the close vicinity of traffic areas. Lead has remained in soil from the period when it was used in gasoline (Blumer 1978, Majdi and Persson 1989, Hashisho and El-Fadel 2004, Dąbrowski 2016). Lead may have also reached to compost through lead-containing paint that was formerly used, and is peeling off from old buildings (Burgoon et al 1995, Marcus and Elias 1995, Gooch 2002).

Another pollutant heavy metal, arsenic can reach green compost from impregnated wood structures used in cities like power line posts etc., which are treated with chromated copper arsenate (CCA) (Zagury et al. 2003, Sawhney et al. 2006, Hasan et al. 2010, Schwer et al. 2011, Shayler et al. 2017). The uptake of contaminants by edible plant crops from the contaminated soils has been studied and confirmed for arsenic and lead. The heavy metal uptake ratio was dependent on the plant species being higher in lettuce (As) or carrot root (Pb) and lower in tomato fruit for both As and Pb (McBride 2013, McBride et al. 2015).

The plant uptake of heavy metals, PAHs and polychlorinated biphenyls (PCBs) was described by Ma et al. (2016). In the work it was described that the accumulation concentrations of Cd, As and Hg increased in three tested vegetables with increased dosage of composted sewage sludge. Heavy metal accumulation ability was described in the order of celery > lettuce > cabbage, except for Cr. The concentrations of PAHs and PCBs is soil increased with increasing sewage sludge compost addition from 15 tons to 30 tons per hectare but the increase was not significant between addition of 3 tons per hectare and control. The concentrations of PAHs and PCBs in the tested vegetables were shown to be positively correlating with compost addition amounts to the soil (Ma, et al. 2016).

2 Study objectives

The three main objectives of this study were:

Objective 1
To develop and test a new environmentally safe spot-application method for sewage sludge compost and for green compost derived from city greenery with the aim of recultivating abandoned mining areas such as cutover peatlands and former sand or gravel mines.
Objective 2
To ensure that this method meets the limits set by legal acts for disseminating nutrients, heavy metals and pharmaceutical residues into soil.
Objective 3
To develop a solution for spot-improvement of water availability in soil for enhanced seeds germination.

The specific objectives of the current work discussed in the published papers were as follows:

1. To evaluate the applicability of spot-applied sewage sludge compost (in the light of environmental safety) for the recultivation of cutover peatlands through tree seedlings growth responses (**Paper IV**);
2. To evaluate the applicability of spot-applied green compost (in the light of environmental safety) for the recultivation of depleted peat and sand (gravel) mines through tree seedlings growth responses (**Paper II**);
3. To compare the effectiveness of spot-applied fertilizer and spot-applied sewage sludge compost in cutover peatland recultivation (**Paper IV**);
4. To assess the applicability of sewage sludge compost and green compost for recultivation purposes considering their nutrient composition (**Papers II** and **IV**);
5. To assess sewage sludge compost suitability for recultivation purposes considering its content of pollutants (**Paper III**);
6. To test the applicability of spot-applied irrigation in recultivation (**Paper II**);
7. To assess rope-wick roots effect on water capillary rise improvement locally through improvement of seeds germination in mining areas recultivation (**Paper I**).

3 Materials and methods

3.1 Test sites

The tests were performed on three test sites, all within a 40 km distance of Tartu city, Estonia (N: 58°23’; E: 26°43’; sites elevation from sea level was 30-60 m, Figure 1). The two abandoned peatland test sites were located on a depleted peat field used 15 years ago to produce peat for generating energy (cutover peatland area). The depth of the peat was 75 cm on the first site and on the second site 150 cm on average. Under the peat there was clay. The level of groundwater changed during the test period from 40 to more than 100 cm depending on the precipitation. The seedlings were planted on 30 May, 2012 for the green compost test and between 03 and 13 of May 2015 for the sewage sludge compost.

The sand and sandy loam test sites were located on the flattened areas of sand pits on treeless spots open to the south. Groundwater was several meters deep in both cases. All the seedlings were planted on the sandy loam test site on 30 April, 2012 and on the sand test site on 30 May, 2012.

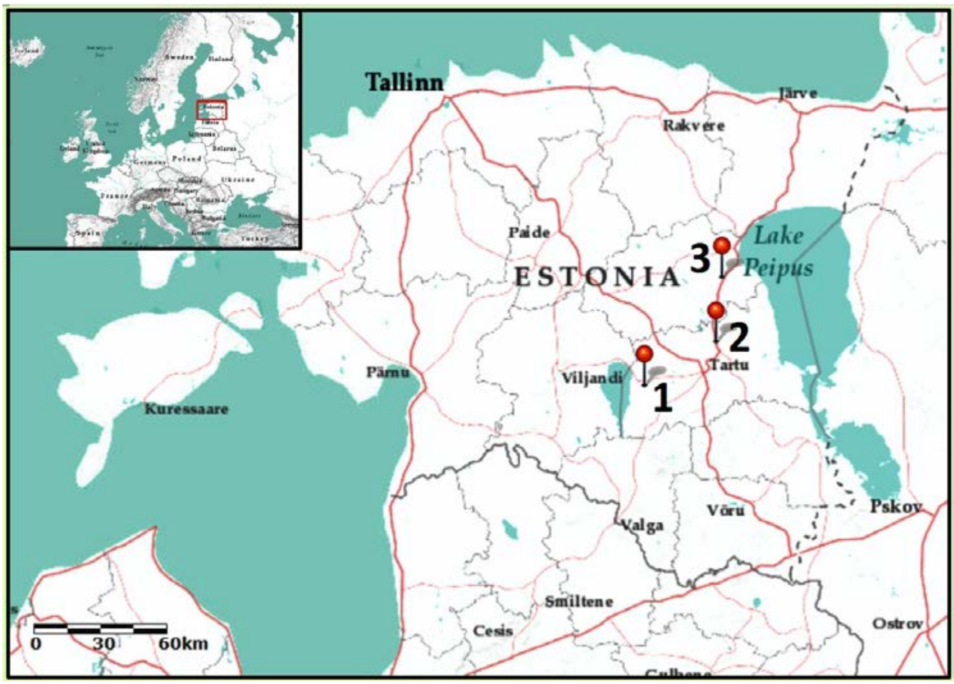


Figure 1. *Location of the test sites (1 – peat, 2 – sand, 3 – sandy loam)*

The following data is provided in Table 1 to give the general climatic background, since plants growth rate is dependent on temperature and water originating from precipitation.

Table 1. *Precipitation and effective temperatures (average day temperature over +5°C) on the green compost test sites summed from 01 April to 31 October during the three year test period (Paper II)*

	Peat		Sandy-loam		Sand	
Year	**Precipita-tion (mm)**	**Sum of effective tempera-tures**	**Precipita-tion (mm)**	**Sum of effective tempera-tures**	**Precipita-tion (mm)**	**Sum of effective tempera-tures**
2012	524	1606	503	1478	510	1571
2013	311	1754	403	1662	345	1802
2014	444	1659	448	1337	476	1723

3.2 Data collection

Precipitation in millimeters and the sum of effective temperatures (average day temperature over +5°C) during the 2012-2014 vegetation periods in the weather stations nearest to the test sites were received. The soil analyses were performed to describe the contents of nutrients in the soils and in the composts applied in the tests. The values of the chemical indicators of soil and compost were determined from the samples as follows: pH_{KCl} (pH was determined in KCl solution) and total nitrogen (N) with the Kjeldahl method (Kjeldahl 1883); available phosphorus (P) content, potassium (K) and calcium (Ca) with flame photometry (Helrich 1990); magnesium (Mg) by flow injection analysis (Page et al. 1982), and soil organic matter content with the method of loss on ignition (Schulte 1995). The compost was classified according to classification provided by Raudväli and Kanger (1996) being with high P and Ca content. The heavy metal concentrations in sewage sludge compost were determined from the samples as follows: zinc (Zn), copper (Cu), chromium (Cr), nickel (Ni), lead (Pb), arsenic (As), and cadmium (Cd) with the standard methods described in European Standard 13657 and ISO 11047:1998, and mercury (Hg) with the standard method described in European Standard 13806.

For comparison with the growth-enhancing effect of the sewage sludge compost, two test series of seedlings with fertilizer additions were also planted (**Paper IV**). The fertilizer was produced by Yara Suomi OY (Yara 2015), product name “Yara Puutarhan PK 3-5-20-13 (with low chloride content)”. The percentages of the fertilizer’s active ingredients were taken from the producer’s analysis.

Volumetric water content in ambient soils and in spot-applied compost was measured to monitor water availability for the seedlings in soil and inside the applied compost. The volumetric water content (VWC) of the soil was measured with a Fieldscout TDR 300 moisture meter (Spectrum Technologies Inc.), the device uses time domain reflectometry as a working principle. Soil moisture was measured by using 200-mm long measuring rods. The 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. The measurement points were in 10 cm 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 closer to the stems without injuring the roots.

Height growth was measured with measurement tape after planting the seedlings and after the growing seasons. The height growth of the seedlings was calculated as the difference of the two measurements. The root length growths were achieved similarly by carrying out initial measurements right after planting and then again after the growing season. The root systems were dug out carefully. All roots were measured from stems to root tips in the ground. The length of the longest leaf was measured as an indicator of growth speed. One estimably longest leaf was taken from each seedling and its length was measured on millimeter paper.

Data analysis was 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 $p < 0.05$.

3.3 Methods of testing novel technologies

3.3.1 Artificial rope-wick roots

Artificial rope-wick roots (**Paper I**) were tested to assist the germinating seeds to receive the water which rises through the wicks by capillary rise effect from lower soil levels (Figure 2). The technical solution was tested to be used on the slopes of amended opencast mines where water deficiency on the surface soil layer is evident and where it is technically difficult to dig holes into planting spots.

Figure 2. *Components of a seed wick-root (left): A - rope-wick, B - wooden support rod, C - binding wire for holding rope attached to support rod and D - paper with coir, seeds and fertilizer; E - assembled wick-root; F and G - wick-roots where mixture of seeds has successfully germinated*

The fertilizer grains were inserted into the coir layer on the soft paper supported by plastic net. The paper and the net were chosen to be easily penetrable by roots. The coir-paper-net was wrapped around the upper end of the wick. Inside the coir, near the fertilizer grains the seeds were placed. The seeds were expected to have suitable conditions to germinate due to good aeration, available water coming through the wick from lower soil layers and due to water dissolved fertilizer carried by the water. The assembly was expected to secure fast root growth of the germinating seeds.

3.3.2 Drill-holes for planting

Planting method for seedlings with 50 cm deep drill-holes filled with compost (**Papers II and IV**) was tested partially for the same reason – to assist the roots of the plants to grow vertically down as fast as possible to secure water availability from the lower soil layers (Figure 3). When the green compost was used (**Paper II**) the drilled holes were filled with compost up to the ground level.

When filling the holes with sewage sludge compost on cutover peatland (**Paper IV**), the drilled holes were filled leaving 10 cm from top for seedlings roots to be surrounded with the back-filled peat. This was a precautionary measure to avoid the roots to be covered with the compost with very high nutrient content which might have caused roots burns. Therefore, only the ends of the roots were placed into contact with the compost. The method also enabled more efficient planting as it was very easy to cover the roots with the softened drilled-out peat (**Paper IV**).

To compare the growth support effectiveness of compost to mineral fertilizer, spot-application of mineral fertilizer was used in two test series (**Paper IV**). The components of the fertilizer are presented in Table 6. In the first fertilizer test series the effect of drilled and back-filled hole was tested (back-filled with the same drilled-out peat). The drilled hole was expected to improve soil aeration and facilitate root penetration in it because the drilled-out peat was softened while unprepared peat was not. For the test series 30 grams of fertilizer was spot-applied into soil in 10 cm distance from the stem, 10-15 cm deep into a poked hole. In the second fertilizer test series the deep hole was not drilled but the same amount of the fertilizer was spot-applied similarly (Figure 3).

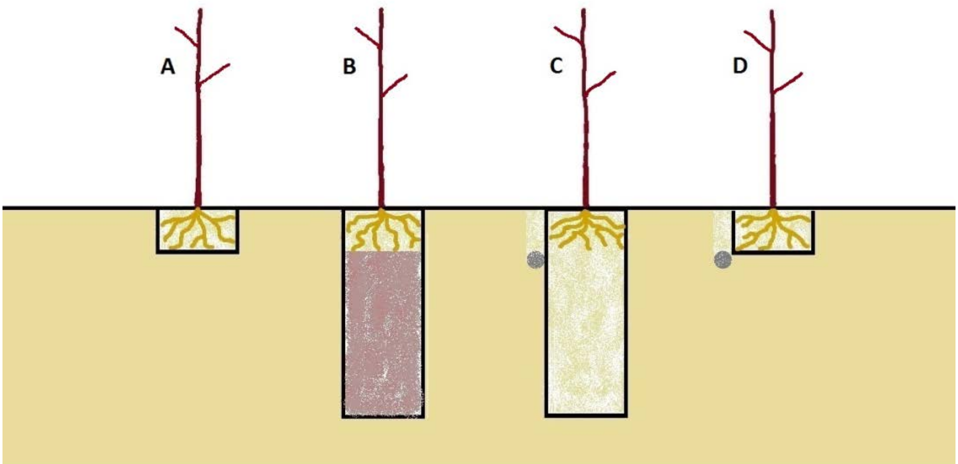


Figure 3. *Description of the treatments:* ***A*** *– a reference seedling planted into peat without adding nutrients;* ***B*** *– a seedling planted into a drill-hole 50 cm deep, with 20 cm diameter, filled with sewage sludge compost, upper 10 cm is back filled with the drilled-out peat;* ***C*** *– a seedling planted into drill-hole with the same size, back filled with the drilled-out peat and granulated multicomponent fertilizer added next to the drill-hole;* ***D*** *– a seedling planted without a drill-hole, granulated multicomponent fertilizer added next to the drill-hole*

When planting into compost-filled drill-holes (**Papers II and IV**), all the compost was inserted only into the drill-holes. The aim of such placing of compost was to provide the seedlings with maximum amount of nutrients, simultaneously avoiding weeds proliferation and directing roots into deeper layers of soil to obtain better water availability/access. The cylindrical-shaped planting holes and the compost additions were designed to guide the roots of the planted seedlings downwards, along with the fertile substrate and towards the moister soil layers. Cylindrical compost additions occupied a relatively small area near the soil surface in comparison to the volume of the same cylinder. Small area of compost additions located near the soil surface reduced the option of weed roots or seeds to get into contact with compost hole-fillings.

3.3.3 Watering

The seedlings were watered without a delay after planting with one to three liters of water to avoid root desiccation when planted into soil which had partially dried or into relatively dry compost (**Papers II and IV**). When the peat was soaked wet during planting (Paper II), the test seedlings which were inserted directly into peat were not watered during planting. No more watering was carried out after planting except in the case of the test group (Paper II) that was watered daily with automated drip-irrigation device.

As part of a test (**Paper II**) a test group of seedlings planted on the compost cylinders were watered daily. The reason for watering was to assess water deficiency influence on seedlings height growth compared to not-watered seedlings. The watering was carried out with a trickle watering device. Water was driven through a thin plastic hose to a dripper near the seedling stem. The battery-driven water pump was switched on for watering three times per day with an electronic timer-guided switch. The amount of water given daily to each watered seedling was one liter.

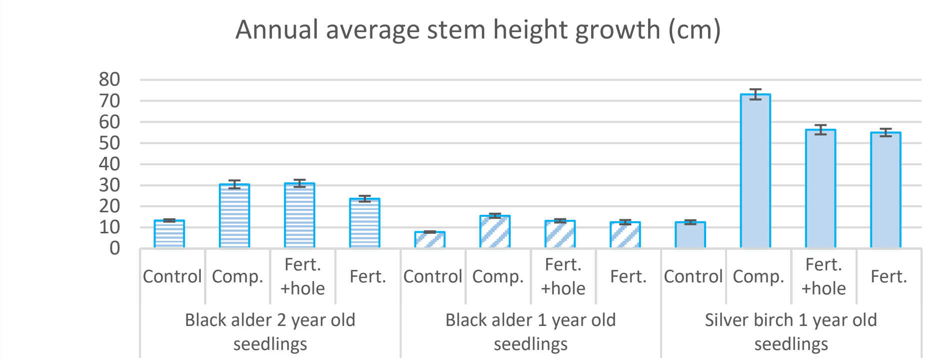
4 Results and discussion

4.1 Growth enhancement with sewage sludge compost and fertilizer (Paper IV)

One of the aims of the current study was to evaluate the applicability of sewage sludge compost as a targeted spot-amendment for recultivation of abandoned cutover peatlands soils with forest tree seedlings. The success of recultivation was assessed by the dimensions growth of the seedlings (height growth of stem and horizontal and vertical growth of roots).

Silver birch seedlings were more sensitive to the growth enhancing treatments (Figure 4) than black alder seedlings. The best results of silver birch seedlings dimensions growth were obtained with sewage sludge compost in the drilled holes. The second best results were evident with drilled holes and spot-applied multicomponent fertilizer followed by the results obtained in the case of spot-applied multicomponent fertilizer only, without drilled holes. The least dimensions growth was achieved by the reference group seedlings without any treatment. The sequence is apparent in the case of stem height, vertical root growth and leaf size (Figures 4–6). The growth differences were significant, at least at the $p = 0.05$ level in most cases. For the levels of significance, see Tables 2–4. The significant growth-promoting effect of treatments can also be seen in both of the black alders longest average leaf lengths and the one-year-old black alder vertical root depths.

The height growth of compost-treated silver birch seedlings (73 cm) was significantly higher than fertilizer-treated seedlings ($p < 0.001$) (56 cm with hole and 55 cm without hole). This finding suggests that when planting silver birches in peat it is advisable to fertilize them with sewage compost rather than applying mineral fertilizer. Compost-induced improvements in height growth were weak for one-year-old black alders (+ 3 cm) and were missing for two-year-old black alder seedlings (-1 cm) compared to the fertilizer-in-hole treatment group (Figure 4).



	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 4. *Annual average height growth (cm) of seedlings with different treatments. Abbreviations:* ***Control*** *– reference seedlings planted without treatment;* ***Comp.*** *– test seedlings planted into compost-filled holes;* ***Fert.+hole*** *– test seedlings planted into back-filled 50-cm-deep, 20-cm-diameter holes with spot-applied fertilizer;* ***Fert.*** *– test seedlings with spot-applied fertilizer;* ***SE*** *– standard errors of average height growth (cm), error bars on graph represent standard errors;* ***Number*** *– number of seedlings measured.*

Differences in annual average height growth were significant between most series of two-year-old black alder seedlings except with the compost and fertilizer-in-hole treatment groups (Table 2). With one-year-old black alder seedlings, annual average height growth differences were significant between the reference group and the rest of the treatment groups, and between the compost and fertilizer-only treatment groups. With one-year-old silver birch seedlings, all treatments showed significantly different average annual height growth results except between the fertilizer-in-hole and fertilizer treatment groups (Table 2).

Table 2. *Comparison of T-test p-values for differences in significance of average stem height growth. P-values < 0.05 are shown in bold*

Treatment	Black alder 2 y	Black alder 1 y	Silver birch 1 y
Reference			
Compost	**< 0.001**	**< 0.001**	**< 0.001**
Fertilizer in hole	**< 0.001**	**< 0.001**	**< 0.001**
Only fertilizer	**< 0.001**	**< 0.001**	**< 0.001**
Compost			
Fertilizer in hole	0.852	0.063	**< 0.001**
Only fertilizer	**0.004**	**0.035**	**< 0.001**
Fertilizer in hole			
Only fertilizer	**0.001**	0.619	0.629

According to Figure 4 and Table 2, significant and remarkable height growth improvement (30-33%) was evident with compost treatment for silver birch seedlings compared to fertilizer treatments.

Increments of root lengths in vertical direction were significantly shorter in all the reference groups compared to almost all 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 Figure 5 and Table 3). Compost treatment resulted in significantly deeper roots compared to the other treatments with silver birches. The roots of all 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.

Increments of root lengths in horizontal direction showed significantly longer root growth with all silver birch test groups compared to the reference group. The compost group had significantly longer horizontal roots' increments (122 cm) compared to the fertilizer-in-hole group (94 cm), (Figure 5, Table 3). The seedlings treated only with fertilizer had a bit longer horizontal root length increment on average (102 cm) than the fertilizer-in-hole group. The root systems of seedlings in the fertilizer-in-hole treatment group were distributed a little deeper instead of growing in horizontal direction. For the silver birches within compost test group, the average roots growth in horizontal direction was 1.22 meters. The distance between the planted seedlings with 2000 plants per hectare is 2.24 meters. Hence, the horizontal roots of compost-applied seedlings meet halfway between the seedlings already at the end of the first growing season, covering most of the peat area between the seedlings and made the colonization of the area by other plant species more difficult.

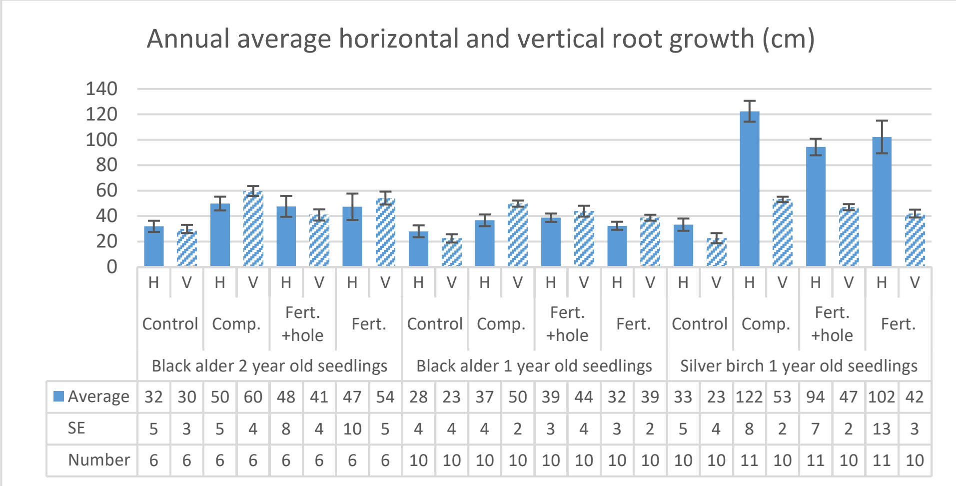


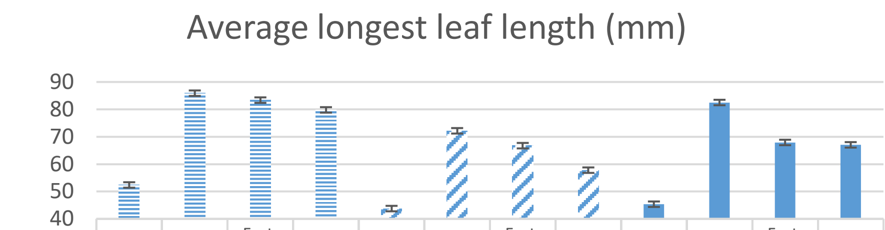
Figure 5. *Comparison of the average root length growth (cm) in horizontal **(H)** and vertical **(V)** directions: **SE** – standard errors of average root length (cm), error bars on graph represent standard errors; **Number** – number of seedlings measured. For abbreviations see Figure 4*

When horizontal root growth of one- and two-year-old black alders was compared, significant differences were identified between reference and compost treatments. Differences were also significant between reference and fertilizer-in-hole treatments with one-year-old black alder seedlings. There were no significant differences between roots lengths (both in horizontal and vertical directions) with fertilizer-in-hole and only fertilizer treatments (Table 3).

Table 3. *Comparison of T-test p-values for differences in significance of average root length growth (coarse and fine roots together). P-values < 0.05 are shown in bold*

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

The trend in average longest leaf length in all seedling groups, from the longest to the shortest, was determined for treatments as follows: compost > fertilizer-in-hole > only fertilizer > reference (Figure 6).



	Black alder 2 year seedlings				Black alder 1 year seedlings				Silver birch 1 year seedlings			
	Control	Comp.	Fert. +hole	Fert.	Control	Comp.	Fert. +hole	Fert.	Control	Comp.	Fert. +hole	Fert.
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 6. *Comparison of the average longest leaf lengths (mm):* ***SE*** *– standard errors of average longest leaf length (mm), error bars on graph represent standard errors;* ***Number*** *– number of leaves measured - one leaf from a seedling. For abbreviations see Figure 4*

There were significant differences between the longest leaf lengths of the reference and all test groups. The longest leaves of compost-treated seedlings were also significantly longer than with both fertilizer-treated seedling groups in the case of the one-year-old black alders and silver birches (Table 4).

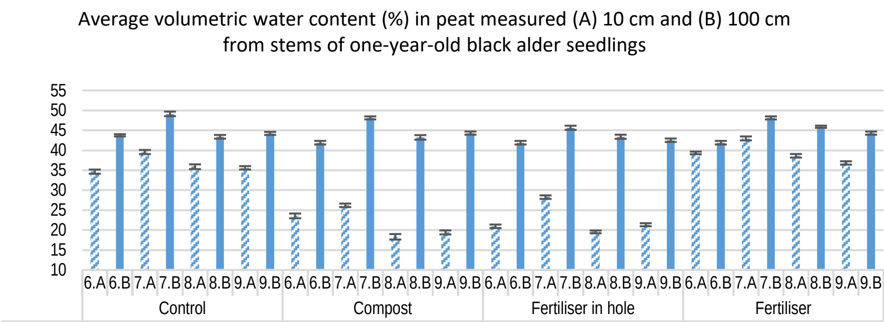
Table 4. *Comparison of T-test p-values for differences in significance of average longest leaf lengths. P-values < 0.05 are shown in bold*

Treatment	Black alder 2 y	Black alder 1 y	Silver birch 1 y
Reference			
Compost	**< 0.001**	**< 0.001**	**< 0.001**
Fertilizer in hole	**< 0.001**	**< 0.001**	**< 0.001**
Only fertilizer	**< 0.001**	**< 0.001**	**< 0.001**
Compost			
Fertilizer in hole	0.340	**0.014**	**< 0.001**
Only fertilizer	**0.013**	**< 0.001**	**< 0.001**
Fertilizer in hole			
Only fertilizer	0.152	**< 0.001**	0.782

In the current study (**Paper IV**), in most cases (ca 95%) neither sewage compost fillings nor the spot-applied fertilizer resulted in weed growth around the seedlings. In ca 2% of the cases the weeds grew high enough to create competition for light with the tree seedlings (they were as high as, or higher than the seedlings). It is important to emphasize that the sewage sludge was thermally treated before composting (at 70°C for an hour). It was evident that the seeds of the weeds in it had lost their ability to germinate.

In **Paper IV**, the average volumetric water content (VWC) values near the seedling roots (10 cm from stems) at the peat test site were always significantly smaller than when measured in equal distances between stems (one meter from stems), see Figure 7. Monthly measurements of VWC were taken from June to September 2014.

Volumetric water content was remarkably lower, being 18–28% 10 cm from the stems of the compost- and fertilizer-in-hole treatment seedlings with all types of planting material. In comparison, VWC of 42–49% was measured in 100 cm distance from stems. There were no drilled holes for the reference and fertilizer-only treatment groups; their volumetric water content was 35–43% 10 cm from the seedling stems. Water consumption 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.



	Control								Compost								Fertiliser in hole								Fertiliser							
	6.A	6.B	7.A	7.B	8.A	8.B	9.A	9.B	6.A	6.B	7.A	7.B	8.A	8.B	9.A	9.B	6.A	6.B	7.A	7.B	8.A	8.B	9.A	9.B	6.A	6.B	7.A	7.B	8.A	8.B	9.A	9.B
Average	35	44	40	49	36	43	36	44	24	42	26	48	18	43	19	44	21	42	28	46	20	43	21	43	39	42	43	48	39	46	37	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	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	114	89	114	90	113	89	114	114	113	112	113	112	113	113	113	113	113	112	113	113	113	113	113	113	113	112	113	112	113	113	113	113

Figure 7. *Comparison of volumetric water content (%) (**Paper IV**). Numbers in front of **A** and **B** indicate the month of the measurement (for example, 7 indicates July). **SE** – standard errors of average volumetric water content measured in soil (%), error bars on graph represent standard errors; **Number** – number of measurement points*

The concentrations of nutrients in sewage sludge compost (in absolute dry matter) used for filling the planting holes in the peat on the cutover peatland test site and concentration of nutrients in the peat (0–10 cm and 40–50-cm-deep peat layers) are given in Table 5.

Table 5. *Initial concentrations of nutrients in the sewage sludge compost and destination peat where the compost was inserted (both in absolute dry matter)*

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

To estimate if the concentrations of heavy metals in the sewage sludge compost were not too high to hinder the growth of the test seedlings, (Paper IV) the concentrations of heavy metals were checked from measurement protocol and also compared to the limit values in the currently valid regulation (Regulation 2002) (Table 6).

Table 6. *Concentrations of heavy metals in the sewage sludge compost used in the planting test and limit values allowed (both in absolute dry matter)*

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

The **applied multicomponent fertilizer** in fertilizer test series was specially designed for usage on peat soils and contained a variety of micronutrients. The list of components of the fertilizer is given in Table 7 (**Paper IV**).

Table 7. *Nutrients in the fertilizer that was used in planting of the spot-applied fertilizer test groups of seedlings*

Element	Gravi-metric %	Element	Gravi-metric %	Element	Gravi-metric %	Element	Gravi-metric %
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	Molybdenium	0.01		

A **comparison of amounts of active nutrient ingredients given to test seedlings with compost and with fertilizer** is given in Table 8 (**Paper IV**). In the compost doses the amounts of nutrient ingredients are tens, or hundred times higher compared to the fertilizer dose, except potassium. To balance the relatively small amount of potassium in sewage compost supply, it must be added to the sewage sludge compost.

Table 8. *Comparison of amounts of active ingredients in the fertilizer and in the sewage sludge compost added to seedlings during planting*

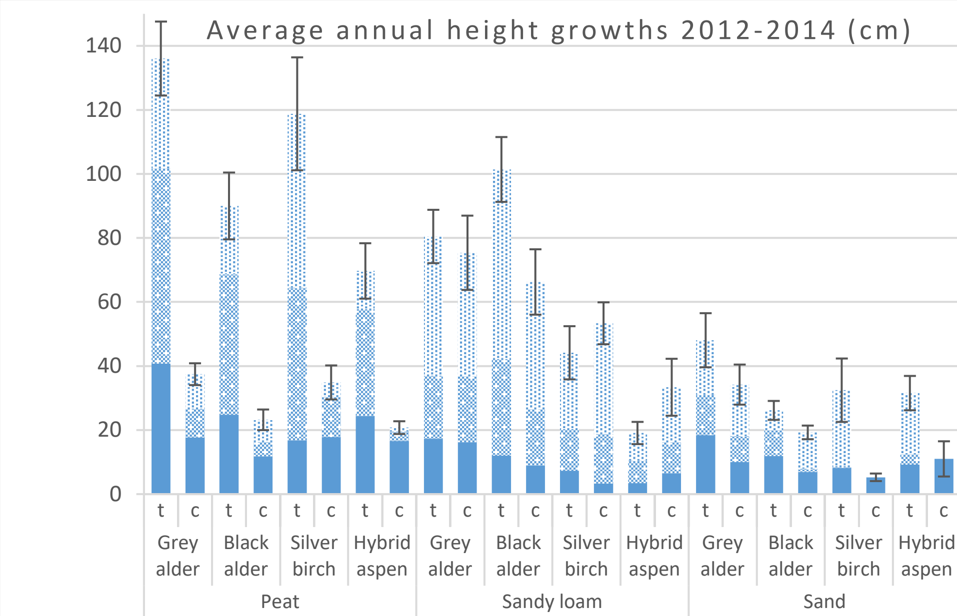
Active ingredient	Amounts of active ingredients in:				Amount of active ingredients in 13.5 liters of compost compared to 30 g of fertilizer (times)
	Fertilizer g kg^{-1}	Compost g kg^{-1} dry matter	Fertilizer g in 30 g	Compost g in 13.5 liters (30% dry matter)	
Nitrogen	32	28.2	0.96	116.1	121
Phosphorus	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

In the current study only 8 tons of dry matter of the sewage sludge compost per hectar was used in case of 2000 planted seedlings per hectar. The difference of the used sewage sludge amount is 45-fold compared to a test where 360 t/ha of sludge (dry matter) was used (Gradeckas et al. 1998). In another example the best results for the one year height growth (52 cm) of silver birch were obtained when 280 t/ha (dry matter) was uniformly mixed into peat with cultivator on cutover peatland (Pikka 2005). The difference in used sewage sludge is 35-fold in this case.

In conclusion, the spot-applied drill-hole fillings of sewage sludge compost appeared to give positive results in recultivation of abandoned cutover peatland. The test results proved that using the compost sparingly by its target-applying enables successful afforestation of abandoned mining lands.

4.2 Growth enhancement with green compost (Paper II)

The suitability of green compost on enhancing seedlings growth was tested by targeted spot-applying it into drill-holes on abandoned mining areas for recultivation purposes. Black alder seedlings with green compost provided significantly higher height growth compared to reference seedlings through three-year growth test on all test sites (peat, sandy loam and sand). It is important to note that there was a high number of dieback of the shoots of untreated seedlings on sand. Therefore, the number of the reference seedlings with positive height growth was too small to be analyzed during the second and third year. On the peat test site almost all the test seedlings of all studied species showed significantly higher height growth compared to the reference seedlings every year except silver birch during the first year (Figure 8).



	Peat								Sandy loam								Sand							
	Grey alder t	Grey alder c	Black alder t	Black alder c	Silver birch t	Silver birch c	Hybrid aspen t	Hybrid aspen c	Grey alder t	Grey alder c	Black alder t	Black alder c	Silver birch t	Silver birch c	Hybrid aspen t	Hybrid aspen c	Grey alder t	Grey alder c	Black alder t	Black alder c	Silver birch t	Silver birch c	Hybrid aspen t	Hybrid aspen c
Number	9	7	10	4	5	3	5	1	20	17	20	19	4	3	5	5	8	6	5	1	2	0	4	0
SE	12	3	10	3	18	5	9	2	8	12	10	10	8	7	3	9	8	6	3	2	10	1	5	6
Σ 3 years	136	37	90	23	119	35	70	21	80	75	101	66	44	53	19	33	48	34	26	19	32	5	32	11
2014	34	11	21	7	54	5	12	1	43	39	59	40	24	35	9	17	17	16	6	11	24	0	19	0
2013	61	9	44	4	48	13	33	3	20	21	30	18	13	15	7	10	13	8	8	1	1	0	3	0
2012	41	18	25	12	17	18	24	17	17	16	12	9	7	3	3	7	18	10	12	7	8	5	9	11

Figure 8. *Comparison of the height growth (cm) of four tree species' test seedlings:* ***t*** *– test seedlings with spot-applied green compost;* ***c*** *– reference seedlings planted without treatment;* ***Peat****,* ***Sandy loam*** *and* ***Sand*** *– soil types of the test sites;* ***Number*** *– number of seedlings that gave positive height growth in third growth year;* ***SE*** *– standard errors of 3 year cumulative height growths (cm);* ***Σ 3 years*** *– height growths of three years summed (2012-2014); error bars represent standard errors*

Different composts have very different nutrient contents. In order to ensure long-lasting nutrient supply to the seedlings, nutrient concentrations must be checked in the used compost. The green compost used in test (**Paper II**) had relatively moderate contents of macronutrients (Table 9).

Table 9. *Initial concentrations of nutrients in the green compost used for filling the planting holes and in the soils on the test sites, in 0-15 cm soil layer (****Paper II****)*

Substrate	pH_{KCL}	Nitrogen %	Phosphorus mg kg^{-1}	Potassium mg kg^{-1}	Calcium mg kg^{-1}	Magnesium mg kg^{-1}	Organic matter %
Green compost	6.72	0.470	325.63	401.32	3622.80	505.87	14.63
Peat	5.39	2.33	0.185	24.62	15307.00	1651.83	70.00
Sand	8.67	0.005	4.31	9.94	1975.10	24.70	0.25
Sandy loam	6.25	0.029	39.10	36.80	338.87	48.69	0.73

In **Paper II,** volumetric water content (VWC) measurements in the peat test area showed that the green compost around the test seedlings roots was significantly drier on average than peat around the reference seedlings roots. The measurements were made in the middle and after the vegetation period. Undisturbed peat between seedlings contained more water in both cases (measured in 1 m distance from the seedlings) (Table 10).

The VWC trend changed on the sandy loam being higher after and lower during the vegetation period in compost around the test seedlings. Water volumetric content was higher in the green compost hole-fillings compared to the surrounding sand on the sand test site both during and after the vegetation period (Table 10).

Table 10. *Average volumetric water contents in soil (%) measured two days after rain (Paper II)*

	Peat test site			Sandy loam test site			Sand test site		
Measure-ment location / measure-ment time	Compost around test seedling	Soil around ref. seedling	Soil without seedling	Compost around test seedling	Soil around ref. seedling	Soil without seedling	Compost around test seedling	Soil around ref. seedling	Soil without seedling
After vegetation period	27	39	43	23	18	20	18	8	8
In the middle of vegetation period	14	28	34	8	9	11	5	3	3

The seedlings growth response when planted on top of the green compost hole-fillings can be expressed as a percentage of seedlings with positive height growths. Test seedlings had the following positive height growths: 97 % cases on peat, 89 % on sandy loam and 70 % on sand compared to reference seedlings (52 %, 81 % and 37 %, respectively).

According to the growth test, green compost can be effectively used as a planting hole filling substance. As a rule, green compost fillings enhanced seedlings growth response in the abandoned mining areas.

4.3 Effect of irrigation on seedling growth (Paper II)

The results of the drip-irrigation test (1 liter per day per seedling) during the 2014 growing season showed improved growth of seedlings on sandy loam. There was statistically significant difference in height growth between irrigated seedlings grown in compost compared to non-irrigated seedlings in compost and the seedlings in untreated soil (Figure 9).

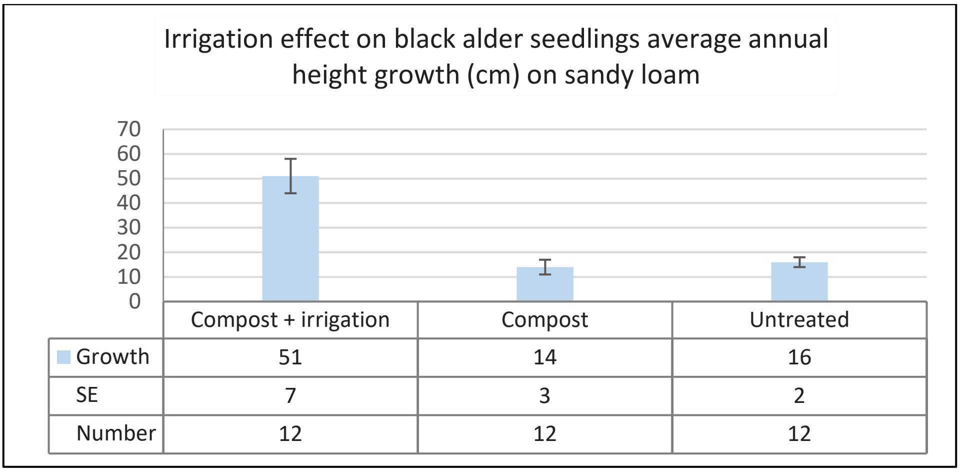


Figure 9. *Average annual height growth (cm) of one-year-old black alder seedlings during irrigation test on sandy loam test site in 2014. Explanation:* ***Growth*** *– height growth (cm);* ***SE*** *– standard error of height growth (cm), error bars represent standard errors;* ***Number*** *– number of seedlings*

4.4 Artificial rope-wick roots (Paper I)

The artificial rope-wick roots improved the germination of four tree species on loamy sand (Table 11). However, a reverse effect was observed on peat soil where seeds sown into soil 0.5 cm deep without artificial wick-roots gave two times higher germination rate. In the case of clay and sand, the germination of all the tree seeds used in the experiments (both in test and reference series) was negligible.

Table 11. *Germination of tree seeds in the wick-roots determined three weeks after planting*

Species	Germination on loamy sand, %			Germination on peat soil, %		
	Seeds with wick-roots	**Seed sets sown 0.5 cm deep**	**Seed sets sown on the surface**	**Seeds with wick-roots**	**Seed sets sown 0.5 cm deep**	**Seed sets sown on the surface**
Norway spruce and Scots pine together	95	53	23	34	67	6
Silver birch	70	23	10	4	7	6
Grey alder	79	41	13	10	21	10

In the current work the rope-wicks gave higher germination rates to the tree seeds on top of the wicks compared to the tree seeds that were sown into surrounding soil on sandy loam. Hence, the wicks improved water availability to germinating seeds by improving upward-directional movement of soil water locally. The rope-wicks did not improve germination of the seeds in sand probably because of inherently low water content in sand, which unables to collect water into wick sufficiently in order to support seeds germination. However, the germination rate was lower in rope-wicks in peat than in surrounding soil probably because the capillary rise of water was higher in peat and the water did not reach easily the rope-wicks. In clay soil the upper layer was very dry during the germination test and small quantities of water that came from lower levels of soil may have evaporated from upper ends of the wicks into the surrounding dry clay soil. Water may have adhered on the clay particles in the surrounding surface layer of clay. Clay has the smallest capillaries and large particle area due to the small clay particles, therefore water loss from wicks into the dry clay can be presumed. Seeds of different species have different need for soil moisture content for germination (Evans and Etherington 1990), therefore if the test were conducted with seeds of other tree species the outcome may have had different results.

4.5 Sewage sludge compost and environmental concerns (Paper III)

In the test performed in the current study (**Paper IV**) where the planting holes were with 20 cm diameter and with 50 cm depth, the sewage sludge compost filling in each planting hole was about 13.5 liters. Dry matter content in the compost was 30.5%, hence dry matter mass in one compost filling was around 4.1 kg. In the recultivation of abandoned mining areas, the number of planting holes may be as high as 2000 per hectare. Consequently, the amount of sewage sludge dry matter applied per hectare is 8,200 kg. That makes 0.82 kg of sewage sludge dry matter per square meter. Including the soil depth of 20 cm and its specific gravity modestly 1.0 into the calculation, 0.82 kg compost divided by 200 kg of soil layer on square meter makes 4.10 grams compost per each kilo of original soil as a result.

For the calculation of the concentration of the pharmaceutical residues in soil, their possible concentrations in sewage sludge compost can be taken from the relevant publications (Lillenberg 2011, Haiba et al. 2016). The highest concentrations of pharmaceuticals detected from city sewage sludge were 2.3 mg/kg in a sample. Pharmaceuticals' degradation rate was assessed to be 99.9% during 12 months composting period. In the case of 99.9% of degradation only 2.3 µg/kg pharmaceuticals remain not degraded. If calculated per square meter it makes 0.01 µg per soil kilogram and it is far below the strictest limit set by Monforts (2005). In the case of 90% degradation 230 µg/kg pharmaceuticals remain in the compost. It makes 1 µg/kg, which is in agreement with Monforts' suggestion and it is ten times less than the 10 µg/kg set by EMEA/CVMP/055/96.

There are other environmental concerns in addition to pharmaceuticals. According to Water Act of Estonia (Water Act 1994), the amount of nitrogen applied with manure per hectare on agricultural lands is limited to 170 kilos annually. The amount of phosphorus per hectare applied with manure is limited to 25 kg annually on average for five years period. The amount of nitrogen found in the sewage sludge compost in current work is 2.82% in dry matter (Table 5). According to Table 5 the peat on cutover peatland had also very similar nitrogen amount (2.78-2.96%) compared to compost (2.82%). Hence, adding sewage sludge compost to the peatland does not increase its original nitrogen content remarkably. In the Water Act the nitrogen limit is set for other soil types than peat that have lower nitrogen concentrations and lower ability to hold nitrogen from leaching, like sandy and loamy soils. In case of 2000 planting holes per hectare with the diameter of 15 cm the compost drill-hole fillings gives 130 kg of nitrogen per hectare. The amount fits in the limit set by the Water Act (170 kg per hectare annually).

The amount of phosphorus found in the sludge compost in the current work was 4880 mg kg^{-1} (Table 5). The amount of phosphorus given with compost would be 22.4 kg per hectare when using the proposed method. This amount is also below the limits set by the Water Act.

The amounts of nitrogen and phosphorus were smaller in the tested green compost (Table 9) compared to sewage sludge compost (Table 5). It means that the requirements set in Water Act are met with the above described planting-hole sizes and numbers per hectare with green compost.

5 Conclusions

In the current work a novel technology was developed and tested to provide a solution for two tasks at once. These tasks were as follows:

1. Need for the recultivation of depleted mining areas;

2. Need for the environmentally reliable utilization of composted waste products.

The three main outcomes of this study are:

1. New spot-application method for sewage sludge compost and green compost derived from city greenery was developed and successfully tested. This method was aimed to provide environmentally safe recultivation of abandoned mining areas, such as cutover peatlands and former sand or gravel mines.

2. The developed method meets the limits set by legal acts for disseminating nutrients, heavy metals and pharmaceutical residues into soil when city-derived sewage-sludge compost is used in the recultivation of abandoned mining areas.

3. Rope-wick artificial roots were developed and successfully tested for improving forest tree seeds germination on loamy sand.

The solution of the tasks listed above is spot−application of composted waste into drilled planting holes with the aim of improving soil properties locally. This approach gives an opportunity to utilize city waste products such as sewage sludge compost and urban green compost in recultivating abandoned mining areas. According to the novel technology the waste products are used sparingly to minimize the polluting effect to the environment, especially to groundwater. The waste products are used more effectively by target-applying them to the exact spots where they are needed instead of spreading them uniformly over the area. As a result of this work the developed and tested rope-wick roots showed improvement in the germination of forest tree species seeds on loamy sand, but not on peat or sand.

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Abstract

Novel Technology for Utilization of Solid Organic Waste in Recultivation of Abandoned Mining Areas

A novel technological and environmentally more sustainable approach was developed and tested to provide a solution for two different problems simultaneously:

(1) Recultivation of abandoned mining areas;
(2) Need for the environmentally secure utilization of composted waste products.

The proposed and tested solution was spot-applying of waste compost into drilled planting holes with the aim of improving soil quality locally. This approach gave an opportunity to utilize city waste products, such as sewage sludge compost and urban green compost, in recultivating abandoned mining areas. According to the novel technology the waste products were used sparingly to minimize the polluting effects to the environment, especially to groundwater. The waste products could be used more effectively by target-applying them to the exact spots where they were needed instead of spreading them uniformly over the area.

As a result of this work, the developed and tested rope-wick roots showed improvement in the germination of forest tree species seeds on loamy sand, but not on peat or sand. In the current work the rope-wicks gave higher germination rates to the tree seeds on top of the wicks, compared to the tree seeds that were sown into surrounding soil on sandy loam. The wicks improved water availability to germinating seeds by improving upward-directional movement of soil water locally. In sand, the rope-wicks did not improve germination of the seeds, probably because of inherently low water content in sand that did not enable water collection into wicks sufficiently. However, in peat, the germination rate was lower when rope-wicks were used because the capillary rise of water was higher in peat and the water did not reach easily the rope-wicks.

The three main outcomes of the current study were:

(1) New spot-application method for sewage sludge compost and for green compost derived from city greenery was developed and tested successfully. The method enables environmentally safe recultivation of abandoned mining areas such as cutover peatlands and former sand or gravel mines.
(2) The new method meets the limits set by legal acts for disseminating nutrients, heavy metals and pharmaceutical residues into soil when city-derived sewage-sludge compost is used in the recultivation of abandoned mining areas.
(3) Rope-wick artificial roots were developed and successfully tested for improving forest tree seeds germination. This approach performed significant beneficial results in the case of loamy sand.

Lühikokkuvõte (Short summary in Estonian)

Tehnoloogia väljatöötamine tahkete orgaaniliste jäätmete kasutamiseks endiste kaevandusalade rekultiveerimisel

Kasutusest väljajäänud kaevandusalade rekultiveerimisel on sageli takistuseks toitainete- ja niiskusepuudus. Toitainetepuuduse korvamiseks on võimalik kasutada reoveesettest või taimsetest jäänustest valmistatud komposti. Seejuures tuleb aga silmas pidada, et selliselt valmistatud kompost sisaldab tavaliselt paljusid "keskkonnavaenulikke" komponente, mistõttu seonduv probleemistik omab määravat tähtsust vastavate tehnoloogiata kasutuselevõtul ja rakendamisel. Niiskusprobleemide lahendamise eesmärgil võeti antud töös kasutusele tahtjuured.

Käesoleva töö põhirõhk oli suunatud jääkturbaalade metsastamisemisega seotud probleemide lahendamisele. Töö käigus võeti uudse lahendusena kasutusele kompostiga täidetud istutusaugud. Selline lähenemine võimaldab oluliselt vähendada keskkonnareostust. Sama meetodit testiti ka liiva- ja kruusakarjääride metsastamisel. Metsapuude seemnete idanevuse suurendamise eesmärgil uuriti mullas sisalduva vee kapillaartõusu lokaalse intensiivistamise võimalusi tahtjuurte abil. Tahtjuurte kasutamine suurendas mitmete metsapuu liikide seemnete idanevust eelkõige saviliival. Käesolevas töös väljatöötatud tehnoloogiad pakuvad uusi võimalusi kasutusest väljajäänud kaevandusalade rekultiveerimisel, võimaldades ühtlasi efektiivselt ja keskkonnasäästlikult utiliseerida reoveesette komposti ja linnahaljastuse tekkivat taimset komposti. Linnade heitvee puhastamisel eraldatakse reoveesete ning see kas põletatakse, laotatakse prügilatesse või sageli kompostitakse. Kompostimise abil lagundatakse reoveesettes sisalduvaid kahjulikke ühendeid, vähendatakse tervistkahjustavate mikroorganismide hulka ning muudetakse reoveesettes sisalduvad toitained taimedele kergemini omastatavaks. Kuna reovee puhastamise käigus eraldatava reoveesette koguse pidurdamatu kasv on kujunenud globaalseks probleemiks, siis selle kasutamisega seotud väljakutseid ei ole inimkonnal võimalik ignoreerida. Vaatamata sellele, et reoveesette kompost on väga toitaineterikas, ei sobi see alati mullaviljakuse tõstmiseks põllumajanduses, sest toidutaimede kasvatamisel võib sellise kompostiga väetatud põllul saak keemiliselt või bioloogiliselt reostuda. Toidutaimed võivad omastada kompostiga segatud mullast mitmesuguseid tervisele kahjulikke aineid, näiteks raskemetalliühendeid ja ravimijääke. Samuti võivad toiduks tarvitatavate taimeosade pinnad saastuda tervistkahjustavate mikroobidega. Võiks arvata, et valdkonnaks, kus põllumajandusega sarnaseid riske seoses reoveesette- ja haljastuskomposti kasutamisega pole, on kasutusest väljajäänud kaevandusalade metsastamine. Paraku aga võib komposti suuremates kogustes kasutamise korral kaevandusalade rekultiveerimisel ikkagi tekkida märkimisväärne keskkonnareostus: kompostis sisalduvad reoained satuvad nii pinna- kui ka põhjavette ja taimedesse ning nendest omakorda loomorganismidesse ja inimese toidulauale.

Nii taimse komposti kui ka reoveesette komposti kasutamine istutusaukudes tagas esimese kasvuaasta jooksul kõrgemad aastased tüve kõrguskasvud ning enamasti ka juurte vertikaalsed ja horisontaalsed kasvud võrreldes kontrollgruppidega. Istutatud puutaimede mõõtmete kiire kasvu saavutamine on oluline majanduslikult, samuti on see vajalik, et saavutada konkurentsieelis võimaliku ümbritseva rohttaimestiku ees. Vastasel juhul tuleb teha pikaaegseid kulutusi umbrohu tõrjele, muidu võib rohttaimestik aeglaselt kasvavad puutaimed aja jooksul välja tõrjuda. Reoveesette komposti ja haljastuskomposti on otstarbekas kasutada mullaomaduste paikseks parandamiseks

ammendatud kaevandusalade rekultiveerimisel. Üldkokkuvõttena võib väita, et käesolevas töös väljatöötatud tehnoloogia mullaomaduste lokaalseks parandamiseks võimaldab olulisel määral vähendada reoveesette komposti või taimsetest jäänustest valmistatud komposti kasutamisega kaasnevat keskkonnareostust kaevandusalade rekultiveerimisel ning annab positiivseid tulemusi lehtpuude seemikute kasvu kiirendamisel.

Appendix 1

Paper I

Jüri Järvis; Mari Ivask; Lembit Nei (2012). Artificial rope-wick roots improve the germination and establishment of tree species. Seed Science and Technology, 40 (3), 433−436.

Jarvis, J., Ivask, M. and Nei, L. (2012), *Seed Sci. & Technol.,* **40**, 433-436

Research Note

Artificial rope-wick roots improve the germination and establishment of tree species

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Summary

Direct seeding is an alternative method to conventional planting for woodland establishment that has several potential advantages. However, a major drawback of this approach is that there is often desiccation of the seeds. To overcome this problem a novel seed sowing technology was developed and tested, that involved artificial roots made of rope-wicks. Each wick root test included a mixed sample of seeds of Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*), silver birch (*Betula pendula*) and grey alder (*Alnus incana*). Rucola (*Eruca sativa*) seeds were added to monitor germination conditions. It was shown that the seeds ability to germinate in relatively dry soil can be enhanced using the artificial roots by improving the capillary rise of water from deeper soil levels.

Experimental and discussion

Although direct seeding is a potentially cheaper method of woodland establishment than conventional planting, it is often considered to be less reliable. The main factor limiting seed germination is thought to be drying of the top layers of the soil (Castro *et al.,* 2004; Bolibok and Andrzeczyk, 2008). Both water and nutrient deficiencies often characterise the sites used for reforestation. Forest tree seeds are sown usually on the ground or up to 1 cm deep depending on the tree species and sowing method. The soil's top layer desiccates during warm and windy periods easily and puts germinating seeds and seedlings at risk, depriving them of the water necessary for vital functions (Oleskog *et al.*, 2000; Oleskog and Sahlén, 2000; Chantal, 2003; Hille and Ouden, 2004; Pamuk, 2004).

While conditions during the first vegetation season substantially influence subsequent growth (Winsa and Sahlén, 2001), it is important to create favourable conditions for emerging plants in order to achieve a higher level of bio-production and rate of survival in the tree community. Current techniques for enhancing water availability for small plants and seedlings are based on adding a super-absorbent into the soil near the roots of the plants. Pamuk (2004) published results for *Pinus sylvestris* L. seeds germinated using short wick-roots (up to 6 cm) made of powdery superabsorbent material. In Pamuk's study the powder also worked as a water holding medium.

The aim of the work presented here was to verify the hypothesis that the seeds ability to germinate in relatively dry soil can be enhanced by improving local capillary rise of water and nutrients from deeper soil levels with artificial roots. Seeds were supplied with rope-wicks (artificial roots) and growth substrate granules. This approach was expected to support the seeds germination and the subsequent development of plants due to the larger water supply present in deeper soil layers.

An acorn of English oak (*Quercus robur* L.) was used as the model for our seed granule due to its sufficient nutrient supply and remarkably deep root (radicle). Seed granules were assembled from rope-wicks, support rods, growth substrate packets, fertilizer and seeds (figure 1). Capillary rise of soil water was secured by using special hollow cotton wicks. The artificial wick was attached to the support rod. The seed granule was shaped like a hollow cylinder, 5 cm long with a 1 cm inner diameter and a 2.5 cm outer diameter. The granules were prepared from a substrate made from coir covered by soft paper and shade cloth (as a supporting net). The substrate was to provide seeds with moisture and nutrients. The shade cloth located in the lower part of the granule enabled the roots to penetrate through its openings. The sprouts were mostly able to penetrate the soft paper covering the upper part of the granule. The 40 cm long support rod was made from wood with and had a diameter of 4.5 mm.

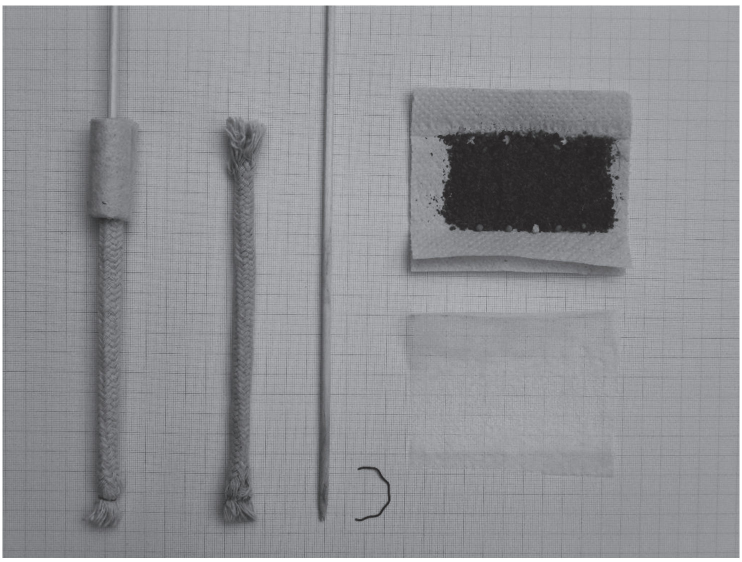

Figure 1. Assembled test granule (left) and its components: rope-wick, support rod, binding wire, paper with coir, seeds and fertilizer and support net. Background is graph paper with one line per mm and cm index lines.

Seeds of Norway spruce (*Picea abies* L.), Scots pine (*Pinus sylvestris* L.), silver birch (*Betula pendula* Roth) and grey alder (*Alnus incana* L.) were inserted into the granules. Rucola (*Eruca sativa* Mill.) were also added to evaluate the conditions under which germination could take place; under favourable conditions rucola seeds germinate in just two days. The number of seeds inserted into one granule was no less than five for the forest tree species and no less than three for rucola. The test granules were planted up to their upper brims into holes poked into the soil. The holes were made using a simple tool designed to create a suitable hollow compartment for the wicks and the granules. Reference tests were conducted with the same sets of seeds, but without inserting them into granules; these seeds were sown simultaneously on the ground and approximately 5 mm deep nearby each granule. Four test sites were selected according to soil type as follows: (1) moist loamy sand (newly clear-cut forest); (2) peat (depleted peat field); (3) clay soil (on agricultural land); and (4) sand (in depleted sand and gravel mine). The total number of granules was 400, and the total number of sets of seeds used for reference tests was accordingly 800. The germination of seeds was assessed three weeks after sowing.

Germination of all the tree seeds inserted into granules sown into loamy sand was excellent (70-95%; table 1). The comparable experiments (seed sets sown 0.5 cm deep) resulted in lower germination (23-41%). These results clearly show that better water availability was secured through wicks. Surprisingly, on the peat soil the germination of seeds inserted into granules was approximately half that of seeds sown not in granules at a depth of 0.5 cm. The reason might be that the evaporation of water from the upper part of the granules was higher than its replacement through wicks and/or there was better aeration of seeds 0.5 cm deep in the soil compared with wick granules. The seed sets sown on the peat surface showed very low ability for germination due to the lack of humidity of the surface layers of this soil type. In the case of clay and sand, the germination of all the tree seeds used in the experiments was negligible. At the same time, the germination of rucola seeds in granules was excellent in all the experiments (between 80 and 95%; data not shown). The germination of rucola seeds not in the granules was negligible except when seeds were sown 0.5 cm deep in loamy sand when there was 44% germination.

The proposed solution of using wicks made of ropes in order to conduct water from deeper layers to the seeds rather than to store water near seeds is a completely novel and more efficient approach, compared with existing technologies.

Table 1. Germination of tree seeds determined three weeks after planting.

Species	Germination on loamy sand, %			Germination on peat soil, %		
	Granules	Seed sets sown 0.5 cm deep	Seed sets sown on the surface	Granules	Seed sets sown 0.5 cm deep	Seed sets sown on the surface
Norway spruce and Scots pine together	95	53	23	34	67	6
Silver birch	70	23	10	4	7	6
Grey alder	79	41	13	10	21	10

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Appendix 2

Paper II

Jüri Järvis; Mari Ivask; Lembit Nei; Annely Kuu; Aarne Luud (2016). Effect of Green Waste Compost Application on Afforestation Success. Baltic Forestry, 22 (1), 90−97.

Effect of Green Waste Compost Application on Afforestation Success

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Abstract

The impact of soil amelioration with green waste compost in the afforestation of depleted peat fields and sand pits was studied. Drilled planting holes (50 cm deep, 20 cm in diameter, 15.7 litres in volume) were filled with fertile compost soil. Containerized yearling seedlings of *Alnus glutinosa* (L.) Gaertn., *Betula pendula* Roth and *Populus tremula* (L.) × *P. tremuloides* Mischx. or bare-rooted ones of *Alnus incana* (L.) Moench were planted into the compost-filled planting holes (test seedlings) and control seedlings into untreated soil. The test growth period lasted for three consecutive growing seasons in 2012–2014.

Compost increased significantly the total three-year height growth of the test seedlings compared to the control ones on the depleted peat mine test site in all four species studied. A significant increase in the total three-year height growth of the test seedlings compared to control ones was also observed in black alder on the sandy loam and sand test sites. A high mortality rate was observed on the sand test site among control seedlings of black alder and among silver birch and hybrid aspen, both test and control seedlings. An irrigation test on sandy loam test site (2014) gave significantly improved height growth to the tested black alder seedlings.

Keywords: green waste compost; compost application; planting seedlings; planting site; height growth; soil aeration; water retention.

Introduction

In Estonia, the renewable energy sectors are priority areas for ensuring sustainable development (Wilkins et al. 1998). The reforestation of depleted peat and sand mining areas is often complicated due to the unfavourable physical, chemical and biological properties of soils. On peatlands, nutrient deficiencies or imbalances, low aeration and excess water content can restrict the growth of seedlings (Pearson et al. 2011). In depleted sand mines (sand pits), lack of water and nutrients are limiting factors for afforestation. The topsoil may easily desiccate during warm and windy periods, and planted tree seedlings face the risk of unsuccessful growth (Castro et al. 2005, Close et al. 2005).

There are several methods that enable better water retention in sand soil. For example, inserting approximately 1 cm thick manure-based organic layers 45-60 cm deep into the sand can accumulate rainwater on the organic barriers and enable cereal plants (rye and wheat) to produce double grain yield compared to test sites, where the same amount of manure was mixed into the upper 25 cm of sand (Egerszegi 1964). Underground water percolation barriers are made from sheet plastic (Smucker 2012) or a layer of asphalt a few millimetres thick (Saxena et al. 1969, Palta and Blake 1974). Hydrogel superabsorbent materials are used for improving sandy soils water retention properties (Singh et al. 2011, Shahid et al. 2012). Different mulching solutions using plastic, ridges and furrows for preventing water evaporation with a combination of rainwater collecting abilities are also tested (Wang et al. 2009, 2011). Usage of the water retention ability of modified clay was analysed by Zhang and Wang in 2013. Usage of Biochar as a water retention medium in soil was tested in sandy loam soils (Ulyett et al. 2014). In the case of low water retention ability only in the upper layer of soil, conducting plant root growth through the dry upper soil layer to deeper moist layers levels has been successful by using artificial wick-roots (Jarvis et al. 2012).

Watering planted forest trees to ensure adequate root development and initial growth is suggested by Goor and Barney (1968). The root systems of plants are able to perform water redistribution in soil upwards, downwards and horizontally using hydraulic redistribution. Hydraulic redistribution is described by several authors as a passive water movement through roots from moister soil areas or layers to roots and exiting roots in soil in areas with lower water potential (Caldwell et al. 1998, Schulze et al. 1998, Brooks et al. 2002, Liste and White 2008).

The mechanism anticipated to support further tree growth is expected to work as follows: if the roots extend into the surrounding soil with the help of nutrients achieved from the extended substrate supply, the bacterial and mycorrhizal fungi communities that exist in the applied compost will spread out into the surrounding nutrient-poor soil along the growing roots. The bacterial and mycorrhizal fungi communities use tree root exudates to survive. Several authors (Uroz et al. 2009, Calvaruso et al. 2010, Zhang et al. 2014) have found that the bacterial communities inhabiting the areas around the tree roots and using root exudates for nutrition can decompose soil minerals making soil more versatile and more suitable for further growth of the same trees. Decomposition of soil mineral particles is also performed by mycorrhizas (Hagerberg et al. 2003, Yuan et al. 2004, Schöll et al. 2008). In addition to bacterial and mycorrhizal fungi communities around the roots, root exudates also cause mineral decomposition of the surrounding poor soil components into the forms with higher assimilability for the same trees by themselves (Dakora and Phillips 2002).

All selected four tree species: grey alder (*Alnus incana* (L.) Moench), black alder (*Alnus glutinosa* (L.) Gaertn.), silver birch (*Betula pendula* Roth) and hybrid aspen (*Populus tremula* (L.) x *P. tremuloides* Mischx.) are able to regenerate from roots or stumps after cutting (Uri et al 2010). Alder species are pioneer species having ability to accommodate nitrogen-fixing bacterial communities (*Frankia alni*) in root nodules (Claessens et al. 2010).

Though afforestation can be supported with mineral fertilizers, wood or peat ash (Pärn et al. 2009, Kikamägi et al. 2013), the substances would not help mitigate problems with low aeration of the soil and too low or too high moisture. The aim of the current study was to test if these problems could be overcome by local enhancement of growth conditions around the roots of tree seedlings, using nutrient rich and air permeable green waste compost with a good water holding capacity during afforestation. Drilling planting holes and filling them with compost is expected to mitigate the problems with low soil aeration in peat and too low or too high moisture level and lack of some nutrients in all target soils. The hypothesis tested in the current work was that locally enhanced soil conditions around the roots of the planted tree seedlings may enable faster development of the seedlings in poor soil.

Materials and Methods

General description of the test sites

Three test sites within 40 km of Tartu (coordinates: 58°23’ N; 26°43’ E; elevation: 30-60 m above sea level) were studied (Figure 1).

The **peat test site** was located on a depleted peat field that was used 15 years ago for producing peat for energy (cutover peatland area). The test site was adjoined by a 60 cm deep ditch from the west, an area with 6 m tall trees from the north and east and an open treeless area in the south. The depth of peat was 74 cm on average. The peat layer was underlaid with clay. The level of groundwater varied during the test period from 40 to 70 cm depending on the rainwater. All the seedlings were planted on 30 May, 2012.

The **sand and sandy loam test sites** were located on the flattened areas of sand pits with open treeless spots in the south. Groundwaters were several meters deep in both cases. All the seedlings were planted on the sandy loam test site on 30 April, 2012 and on the sand test site on 30 May, 2012.

According to data of the weather stations nearest to the test sites, precipitation in millimetres and effective heat (average day temperature over +5°C) sums during the 2012-2014 vegetation periods are presented in Table 1. These data are provided to indicate the climatic background since plants growth rate depends on solar heat and water received from atmospheric precipitation.

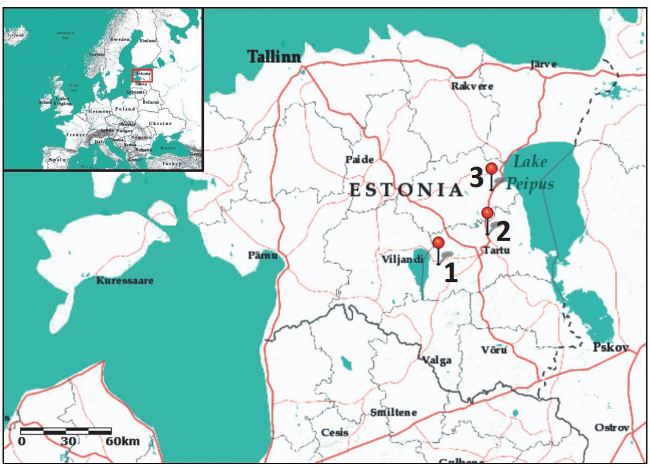


Figure 1. Location of the test sites (1 – peat, 2 – sand, 3 – sandy loam) for assessment of the effect of compost application on the height growth of forest tree seedlings on soils of various types

Table 1. Precipitation in millimetres and effective heat (over +5°C) sum in degrees C on the test sites from 01 April to 31 October during the three-year test period

Soil	Peat		Sandy loam		Sand	
Year	Precipitation, mm	Effective heat sum, deg. C	Precipitation, mm	Effective heat sum, deg. C	Precipitation, mm	Effective heat sum, deg. C
2012	524	1606	503	1478	510	1571
2013	311	1754	403	1662	345	1802
2014	444	1659	448	1337	476	1723

Planting holes and compost

The planting holes were made with soil auger "Stihl BT 121". In order to ensure maximum volume of compost available per plant, the biggest available 20 cm in diameter soil drill was used to drill 50 cm deep planting holes. The volume of each drilled hole was 15.7 litres. Deep planting holes were chosen because earlier tests with containerized seedlings have shown a positive correlation between increased container depth and seedling growth (Close et al. 2005, Chirino et al. 2008). Growing seedlings in deeper containers increases the number of primary roots and improves the plant root system architecture (Nelson 1996). The relatively large planting hole filled with compost was expected to minimize the seedlings transplanting stress by holding water, air and nutrients, as well as enabling the seedlings to form their own root structure as freely as possible. The planting holes were filled with green waste compost and compacted lightly.

Green waste compost used in the tests (its properties are given in Table 2) was produced from only plant-origin residues in the Tartu Tree Nursery. The raw materials of the compost were weeds, grass clippings and peat formerly used for growing forest-tree seedlings in seedbeds. This compost was produced by piling the components and mixing already matured compost into the piles during several years. Plant pathogens in the compost were not investigated.

Moisture and nutrient content in soils and compost

The volumetric water content (VWC) of the soil was measured with a Fieldscout TDR 300 (time domain reflectometry) soil moisture meter using 200 mm measuring rods. Volumetric water content values were measured in 04 October 2012 at the end of growing season to show the difference in VWC between compost additions and test site soils without having transpiration influence from the seedlings. For comparison, the VWC values were measured in the middle of growing season on 22 June 2013 to have a full transpiration impact from the seedlings on water content in soil under compost application and in the original soil. Both measurements were made two days after a moderate rainfall (Table 3).

In Table 2 the values of soil parameters were determined from soil samples as follows: pH_{KCl} (pH was determined in KCl solution), total nitrogen (N) by Kjeldahl method, available phosphorus (P) content, potassium (K) and calcium (Ca) by flame photometry (Helrich 1990), magnesium (Mg) by flow injection analysis (Page et al, 1982) and the soil organic matter content by the method of loss on ignition (Schulte 1995).

On three test sites studied, soils were deficient in several nutrients (Table 2). The planting holes were drilled into the soil and filled with compost (in the Table 2). The N, P, K, Ca and Mg contents in the green waste compost were considered to be high or average for plant growth (Pihelgas 1983, Kevvai 1996, Loide 2008). The concentrations of P and K in the test sites soils are generally considered to be low or very low. A very high nitrogen and very low phosphorus content in peat is common. In this particular peat, the calcium and magnesium contents were also very high, which sets off this peat from the majority of peats.

Planting of seedlings

Twenty black alder (*Alnus glutinosa* (L.) Gaertn.) and grey alder (*Alnus incana* (L.) Moench) seedlings (10 test and 10 control seedlings) were planted on the **peat and sand test sites**. Also, 10 silver birches (*Betula pendula* Roth) and 10 hybrid aspens (*Populus tremula* (L.)×*P. tremuloides* Mischx.) were planted, with 5 test and 5 con-

Table 2. Results of chemical analysis of compost used for filling planting holes and soils from the test sites (soil layer 0-15 cm)

	pH_{KCL}	N, %	P, mg kg^{-1}	K, mg kg^{-1}	Ca, mg kg^{-1}	Mg, mg kg^{-1}	Organic matter, %
Compost	6.72	0.470	325.63	401.32	3622.80	505.87	14.63
Peat	5.39	2.33	0.185	24.62	15307.00	1651.83	70.00
Sand	8.67	0.005	4.31	9.94	1975.10	24.70	0.25
Sandy loam	6.25	0.029	39.10	36.80	338.87	48.69	0.73

trol seedlings planted alternately (60 seedlings in total per test site, 30 test and 30 control seedlings alternately). On the **sandy loam test site**, the number of each species of the seedlings was doubled (120 seedlings in total, 60 test and 60 control seedlings alternately). The distances between the seedlings were 2 m on all sites.

All black alder and silver birch seedlings were grown in containers with dimensions 60×60×80 mm; the hybrid aspen seedlings in containers with 60×80×80 mm. The grey alder seedlings were bare-rooted (grown in nursery). All these seedlings were one year old.

The test seedlings were planted into the centres of the compost fillings of the planting holes. Three litres of water was poured to each planted seedling in each compost soil filling during planting because the compost was too dry for planting. The same number of **control seedlings** were planted directly into the original soil of the test plots (peat, sand and sandy loam). Also, the control seedlings were irrigated with 3 litres of water to provide equal treatment (except control seedlings on peat because the peat was soaked wet at the time of planting). No extra irrigation was carried out after the planting day on any of the test sites.

Irrigation test series on sandy loam

To test the seedlings growth response to higher soil water content on sandy loam, three groups of 12 one year old black alder seedlings were planted on 27 April, 2014. The seedlings of two groups were planted into 1 m deep and 10 cm in diameter holes with compost fillings (with a volume of 7.9 litres). The third (control) group of 12 seedlings was planted into untreated sandy loam soil. For one of the groups with compost fillings, an automatic drip irrigation system was installed (model Irrigatia SOL C-24) that supplied 1 litre of water per seedling per day.

Measurements of height growth

The seedlings growth was monitored by measuring their height with a measuring tape with 1 mm accuracy. The height measurements were made after each vegetation period from 2012 to 2014. All the seedlings with animal browsing damage were excluded from the data. Also, all negative annual height growths were excluded from the height growth analysis.

Statistical analysis

Statistical analyses were performed with the MS Excel 2013 software. Two sample t-tests with assuming unequal variances were used to test the effect of added compost on height growth. All statistical tests were considered significant at the level $p < 0.05$.

Results

Moisture content in soil

Supplied compost in **peat** may provide better aeration compared to the surrounding dense peat layers. Based on volumetric water content (VWC) measurements, the compost around the test plant roots was significantly drier on average than around the control plants roots when measured after the vegetation period (2012) and in the middle of the vegetation period (2013). Undisturbed peat measured in 1 m distance from the control seedlings contained more water in both cases (Table 3).

The VWC trend was changing on the **sandy loam** being higher after and lower during the vegetation period in compost around the test seedlings.

Improvement of the water retention ability of the compost was detected on the **sand** test site both during and after the vegetation period.

Height growth

Black alder seedlings gave significantly higher growth compared to control seedlings through three-year growth test on all test sites. It is important to note that due to a high number of dieback of the shoots of untreated seedlings on **sand** the number of test seedlings with positive height growth was too small to be analysed during the second and third year.

On the peat test site almost all the test seedlings of all species studied showed significantly higher height growth

Table 3. Average volumetric water contents in soils (%) measured two days after rain

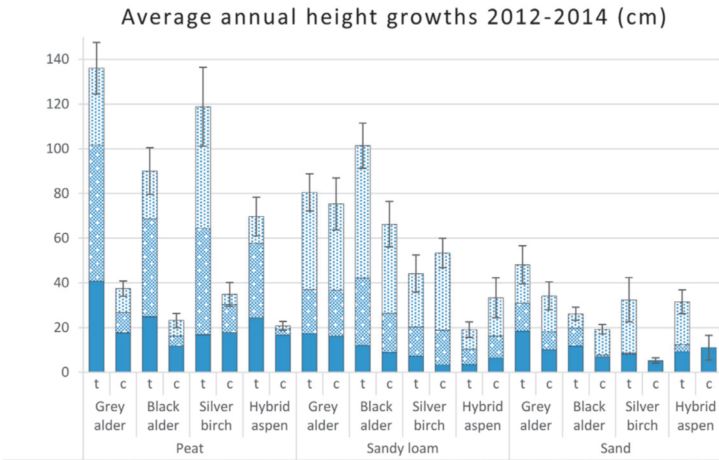
	Peat test site			Sandy loam test site			Sand test site		
Measure- ment location / measure- ment time	Compost around test seedling	Soil around control seedling	Soil without seedling	Compost around test seedling	Soil around control seedling	Soil without seedling	Compost around test seedling	Soil around control seedling	Soil without seedling
After vegetation period	27	39	43	23	18	20	18	8	8
In the middle of vegetation period	14	28	34	8	9	11	5	3	3

compared to the control seedlings every year except silver birch during the first year (Figure 2).

An additional positive effect of compost was also observed on the peat test site. The compost seemed to protect newly planted seedlings from frost heaving. All the seedlings in compost soil were well rooted and stood firmly in the ground, whereas four control seedlings out of 30 were lifted by frost heaving after the first winter after planting. The number of observations is small to draw a conclusion but the result can be considered as an indication.

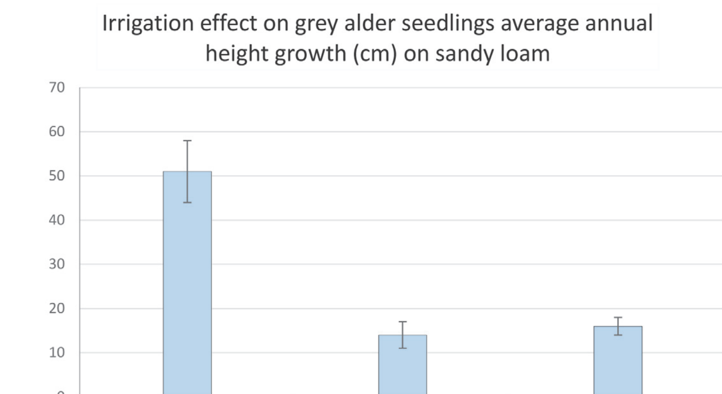
Effect of irrigation

The results of the irrigation test during the 2014 growing season showed a statistically significant difference in height growth between irrigated seedlings grown in compost compared to non-irrigated seedlings in compost and the seedlings in untreated soil (Figure 3).



	Peat, Grey alder, t	Peat, Grey alder, c	Peat, Black alder, t	Peat, Black alder, c	Peat, Silver birch, t	Peat, Silver birch, c	Peat, Hybrid aspen, t	Peat, Hybrid aspen, c	Sandy loam, Grey alder, t	Sandy loam, Grey alder, c	Sandy loam, Black alder, t	Sandy loam, Black alder, c	Sandy loam, Silver birch, t	Sandy loam, Silver birch, c	Sandy loam, Hybrid aspen, t	Sandy loam, Hybrid aspen, c	Sand, Grey alder, t	Sand, Grey alder, c	Sand, Black alder, t	Sand, Black alder, c	Sand, Silver birch, t	Sand, Silver birch, c	Sand, Hybrid aspen, t	Sand, Hybrid aspen, c
Number	9	7	10	4	5	3	5	1	20	17	20	19	4	3	5	5	8	6	5	1	2	0	4	0
SE	12	3	10	3	18	5	9	2	8	12	10	10	8	7	3	9	8	6	3	2	10	1	5	6
Σ 3 years	136	37	90	23	119	35	70	21	80	75	101	66	44	53	19	33	48	34	26	19	32	5	32	11
2014	34	11	21	7	54	5	12	1	43	39	59	40	24	35	9	17	17	16	6	11	24	0	19	0
2013	61	9	44	4	48	13	33	3	20	21	30	18	13	15	7	10	13	8	8	1	1	0	3	0
2012	41	18	25	12	17	18	24	17	17	16	12	9	7	3	3	7	18	10	12	7	8	5	9	11

Figure 2. Comparison of the height growth (cm) of test seedlings "**t**" (with compost application) and control seedlings "**c**" (planted without treatment) belonging to four tree species under study on three test sites with **peat**, **sandy loam** and **sand** soils, respectively.
SE is the standard errors of 3-year cumulative height growths (cm), error bars on graph represent standard errors.
Number is the number of seedlings that gave positive height growth on the third growth year.
Σ 3 years is the resultant height growth during three consecutive years (2012-2014)



	Compost + irrigation	Compost	Untreated
Growth	51	14	16
SE	7	3	2
Number	12	12	12

Figure 3. Average annual height growth (cm) of one-year old grey alder seedlings during irrigation test on sandy loam test site in 2014
Growth is the height growth (cm);
SE is the standard error of height growth (cm), error bars on graph represent standard errors;
Number is the number of seedlings

Growth success ratio

The seedling response to the compost fillings can be expressed as a percentage of seedlings with positive height growths. Test seedlings had the following positive height growths: 97 % cases on peat, 89 % on sandy loam and 70 % on sand compared to control seedlings (52 %, 81 % and 37 %, respectively).

Discussion and Conclusions

On the **peat** test site, the compost added into planting holes was more aerated than the surrounding peat and enabled higher root activity that resulted in faster growth of the test seedlings. The surrounding peat had a higher water content compared to the compost-filled planting holes and acted as a water reserve always available for the roots grown out from the compost. In addition, the high growth of the test seedlings was probably supported by a very high level of nitrogen in the surrounding peat. The practical absence of phosphorous in the peat was compensated by its abundance in the compost. The height growth of the test seedlings was higher during the second growing season, when there was a comparatively low amount of precipitation and relatively high effective temperatures (Table 1). Higher growth of test seedlings with compost addition corresponds to the results of another peatland afforestation test with sewage sediment compost, where compost was spread uniformly over the test area and mixed with peat soil (Pikka 2005). Growth test on peat substrate with added sewage sludge compost and wood ash showed improved growth of willows (Lazdina et al. 2011), which is in accordance with the results of current work.

On the **sand** test site, the addition of compost increased significantly only the height growth of the black alder seedlings during the first two years and silver birch seedlings during the first growing year. Improved height growth can be attributed to better water retention ability and fertility of compost. Similar improvements of water holding capacity in sand soils are achieved with addition of modified clay (Zhang and Wang 2013) or rainwater collecting solutions that use plastic film and changed surface profile (Wang et al. 2009, 2011). Despite better water holding capacity compared to the surrounding sand, the amount of rainwater that accumulated into the compost-filled planting holes was not sufficient to provide a constantly available supply for the test seedlings. Severe drying of the shoot tops (dieback) occurred among the control seedlings of black alder, silver birch and hybrid aspen during the second growing season, when precipitation was comparatively low and effective temperatures were high. Dieback continued during the third growing season despite milder growing conditions. Higher nutrient content in the compost compared to the surrounding sand was expected to accelerate the treated seedlings growth during the period of water availability compared to seedlings without treatment. No significant differences in height growths were observed between grey alder test and control seedlings, however, both had constant and steady growth through three years.

On the **sandy loam** test site, the higher nutrient content in the compost was expected to give a significant effect on the height growth of the test seedlings of all tree species compared to control seedlings. However, the expected trend appeared only with black alder seedlings. The result corresponds to the tests performed with added biochar (Ulyett et al. 2014) or superabsorbent (Singh et al. 2011, Shahid et al. 2012), where the added substances improved water retaining capacity of sandy loam. The suspected water shortages in compost between rainfalls were expected to be the reason for only modest growth improvement with test seedlings in compost fillings. The conducted additional irrigation test (see "Effect of irrigation") seems to avoid a soil water deficit on the test site. However, the current test does not explain the roughly doubled height growth of both test and control seedlings during the third year, despite the precipitation rate being roughly similar and the effective heat sum being smaller than during the previous years.

The study showed the differences in seedlings height growth on test sites and between tree species. All the test seedlings (except silver birch during the first year) gave significantly higher three-year height growth on the peat test site. This result corresponds to the results of the studies (Pärn et al. 2009, Kikamägi et al. 2013) that described improved height growth of silver birch and black alder in response to ash addition. Also, statistically significant differences in height growth between the irrigated seedlings grown in compost compared to non-irrigated seedlings in compost and the seedlings in untreated soil were measured. It confirms the statement that after planting, watering of forest tree seedlings results in their better establishment (Goor and Barney 1968). The hypothesis was confirmed showing that added compost caused significantly improved height growth of some tree species seedlings on some soil types, hence enhanced the growth conditions locally.

Recommendations for future testing

This work was expected to detect which species on which soils can benefit from compost amendment. The number of seedlings used in the tests was rather small and the results of this experiment will be a good starting point for further testing with a larger number of seedlings focusing on species and soils selected based on the results of the current work. Drilling planting holes and filling them with compost can be mechanized and automatized or even robotized to some extent in levelled areas like depleted peat fields and sand. In the case of deep planting holes, root activity should be supported with artificial aeration by embedding perforated plastic pipes into planting holes. In further tests, other kinds of compost can be used, for example, compost of city sewage sediments, which may reduce the price of current afforestation method and help reuse sewage waste. The sewage compost cannot be used for agricultural purposes: it may contain an excess amount of chemical contaminants that can be assimilated by food crops (Lillenberg et al. 2010, Nei et al. 2011). However, sewage compost is rich in minerals, enabling long-lasting supply for the fast growth of plants. Chemical contaminants are expected to be consumed from compost by forest tree plants and accumulated in their timber, enabling to draw pollutants out from circulation (López et al. 2014). The amount of compost needed in the form of the fillings in the planting holes is remarkably smaller and is expected to pose a smaller threat to groundwater through leaching components compared to the method covering the soil with a sewage sediment compost layer for afforestation (Pikka 2005). Automated irrigation systems could be used in a further test on the sand and sandy loam test plots to investigate whether irrigation can increase the effect of compost application on root vertical growth down to more moist soil layers. In sand areas, adding plastic film reservoirs at the bottom of planting holes (filled with porous material like surrounding sand to maintain shape) must be tested for water retaining ability and for plant growth reaction. The plastic water reservoirs under plants may be equipped with filling pipes for adding water during longer dry periods and for water level monitoring. Additional rainwater collection solution consisting in funnel-like sheet-plastic surrounding planted seedlings inside the upper soil layer can be tested together with the reservoirs. Also, a technically easier method of filling the planting holes with liquefied compost (mixed with water) can be tested based on the results of the current work.

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Appendix 3

Paper III

Egge Haiba; Lembit Nei; Mari Ivask; Jane Peda; Jüri Järvis; Merike Lillenberg; Karin Kipper; Koit Herodes. (2016). Sewage sludge composting and fate of pharmaceutical residues – recent studies in Estonia. Agronomy Research, 14 (5), 1583−1600.

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Sewage sludge composting and fate of pharmaceutical residues – recent studies in Estonia

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Abstract. This review is to reflect the work addressed to the application of biosolids and especially sewage sludge as a resource in composting. A considerable drop in the use of P fertilisers can be followed since early 1990s. Due to this fact crop production in Estonia takes place at the expense of soil phosphorous (P) resources. One of the ways of increasing the fertility of agricultural lands is to use nutrient-rich sewage sludge. Unfortunately, this may cause several undesired consequences due to biological and chemical contaminants. The presence of some widely used pharmaceuticals, as ciprofloxacin (CIP), norfloxacin (NOR), ofloxacin (OFL), sulfadimethoxine (SDM) and sulfamethoxazole (SMX), was evident in sewage sludge of the two Estonian largest cities, Tartu and Tallinn. The concentrations of pharmaceuticals decreased after sewage sludge digestion and composting, but they were still present in detectable amounts. Sewage sludge co-composting experiments with sawdust, peat and straw showed the degradation of fluoroquinolones (FQ) and sulfonamides (SA). Additions of sawdust clearly speeded up this process, whereas the mixtures with peat and straw performed lower abilities to decompose pharmaceutical residues. Novel methodologies were developed and experiments conducted to study the potential accumulation of fluoroquinolones FQs and SAs by food plants. Due to the low adsorption of SAs on soil particles they are 'free' to migrate into plants. Different behaviour is characteristic to FQs as they are accumulated in sludge. Recent years have also shown progress in vermicomposting work and in using compost in afforestation.

Key words: composting technologies, fertilizers, pharmaceuticals, plant uptake, sewage sludge, vermicomposting.

INTRODUCTION

Land application of biosolids is generally considered to be the best option of disposal because it offers the possibility of recycling nutrients, provides organic material, improves soil properties, and enhances crop yields (White et al., 2011). Higher soil quality is generally associated with higher concentrations of soil organic matter and a plentiful supply of essential elements. Thus, the recycling of organic matter from anthropogenic residues to soil often benefits agricultural sustainability (White et al., 2013). However, this benefit has to be weighed against potential deleterious effects (White et al., 2011). Whilst recognising its significant value as a resource, recycling sewage sludge to agricultural land requires a careful management to avoid potential negative impacts on the environment from chemical contaminants (Torri et al., 2012).

Organic residues recycling via composting appears to be an ancient activity. The practice of converting animal manure and other biodegradable wastes to compost is believed to have originated as early as agriculture (Fitzpatrick et al., 2005). The earliest known written reference to composting is found in clay tablets dated to the Akkadian empire, about 4,300 years ago (Rodale, 1960), but it is believed that the fertilizer value of aerobically degraded organic matter, which we now call compost, was recognized much earlier. There is evidence that the Romans, Greeks, and the Bani Israel knew about compost. The Bible and Talmud both contain numerous references to the use of rotted manure straw, and mention of compost occurs in 10th and 12th century Arab writings, in medieval Church texts, and in Renaissance literature (Smith et al., 2007).

A worldwide massive use of biosolids as soil conditioners and fertilizers arose in the early 1900s (Frank, 1998). Increasing urbanization and industrialization have resulted in a dramatic growth in the amount of wastes generated globally, particularly of sewage sludge as a byproduct from sewage treatment (White et al., 2011). Land application of treated sewage sludge and other biosolids improves soil fertility and has an important role in closing nutrient cycles (Torri et al., 2012). Among the macronutrients contained in sludge, phosphorus is an essential element for plant metabolism, often considered one of the most limiting nutrients for plant productivity (Shaheen et al., 2012).

A large variety of plant, animal and synthetic wastes can be gainfully composted at scales varying from a household bin to a large industry (Gajalakshmi & Abbasi, 2008). In the composting process, aerobic microorganisms use organic matter as a substrate (Gajalakshmi & Abbasi, 2008). The microorganisms decompose the substrate, breaking it down to more simple compounds (Epstein, 1997; Ipek et al., 2002). During composting, carbon- and nitrogen-containing compounds are transformed through successive activities of different microbes to more stable organic matter, which resembles humic substances (Pare et al., 1998). The rate and extent of these transformations depend on available substrates and the process variables used to control composting (Marche et al., 2003; Gajalakshmi & Abbasi, 2008).

Inventories of soil productive capacity indicate human-induced soil degradation on nearly 40% of the world's arable land (Doran & Zeiss, 2000); this warns us of the ecological collapse of the world's productive soils (Pankhurst et al., 1997). In Estonia the highly industrialised and centralised agricultural production system collapsed in the late 1980s and early 1990s. The area of arable land (crop fields and cultural grasslands) decreased from about one million ha in the early 1990s to less than 0.6 million ha by 2003 (Statistics Estonia, 2006; Iital et al., 2014). Also, a considerable drop in the use of N and P fertilisers took place in the early 1990s when it constituted only about 13% of the peak in 1987–1988. Based on the data from Statistics Estonia in 1994–2001 the average annual consumption of commercial fertilisers was only 85 kg ha^{-1} and in 2009–2011 it reached the level of 120 kg ha^{-1} (Statistics Estonia, 2012; Iital et al., 2014). Since mid–1990s the national average soil P balance has been negative in Estonia due to a sharp decrease in fertilizer use and availability of manure. The national average soil P balance varied in 2004–2009 from -10 to -5 kg P ha^{-1}. Currently crop production in Estonia largely takes place at the expense of soil P resources (Astover & Rossner, 2013).

One of the most efficient ways to eliminate this problem is an intelligent usage of solid waste composts.

This overview is to reflect recent research performed mainly in Estonia in the area of composting. These studies involved different aspects of sewage sludge composting and compost usage; vermicomposting of different waste materials; possible undesired consequences associated with the application of composts in agriculture.

NECESSITY FOR COMPOSTING AND RESOURCES (BACKGROUND)

The soil cover of Estonia is relatively varied due to the alternation of carbonate and humus-rich soils with acid soils which are relatively poor in nutrients and organic matter (Köster & Kõlli, 2013). The lack of nutrients is especially obvious in the case of peatlands which cover 22.3% (10,091 km^2) of Estonia's territory, so restricting the usage of these lands for agricultural purposes. The awareness of the composition and properties of soil cover and its relationship with plant cover in different land use conditions is the basis of ecologically proper and sustainable management of land and soil resource (Köster & Kõlli, 2013).

Estonia has the world's largest exploited oil-shale basin covering about 4% of its territory. In 2001−2013 the number of active landfills in Estonia decreased from 159 to 13. Recultivation of the landscapes covered by semi-coke, oil-shale ash mountains, abandoned opencast mines and closed landfills appears to be one of the major environmental tasks in Estonia.

Biosolids can be used in biofuel production (Raud et al., 2014), leading to the incineration of organic matter. Perceived as a green energy source, the combustion of biosolids has received renewed interest. Still, anaerobic digestion is generally a more effective method than incineration for energy recovery, and digested biosolids are suitable for further beneficial use through land application (Wang et al., 2008). The use of biosolids as a source of organic matter may improve the physical and chemical properties of agricultural soils resulting in an increase in crop yields (Torri et al., 2014). The major potential source for making compost in Estonia is sewage sludge. The yearly generation of sewage sludge by Estonian sewage treatment plants is 30,000 tonnes dw.

Semi-coke is the waste product of oil shale industry and presents the hazard to the environment, due to its phenol and PAH content. One of the main problems of oil shale industry is how to treat semi-coke effectively (Wang et al., 2009). In 1993−2003 the volume of semi-coke formed in Estonian shale oil enterprises varied within 0.6 and 1.4 million tonnes annually (Pae et al., 2005). It has been established that the compost made from semicoke and sewage sludge increases the yield of the crops (Varnik et al., 2006).

The average quantity of biodegradable waste generation in Estonia from grocery stores during 2004–2010 was 9 thousand tonnes $year^{-1}$. The results of SWOT analysis published by Blonskaja et al. in 2014 showed that composting process is the best solution for kitchen wastes. It has been demonstrated that one of the ecologically and environmentally friendly alternatives to traditional technologies in organic wastes management is vermicomposting, especially in kitchen wastes treatment (Ivask et al., 2013; Peda & Kutti, 2013; Haiba et al., 2014; Sinha et al., 2014).

SEWAGE SLUDGE COMPOSTING AND ENVIRONMENTAL CONCERNS

Unprecedented growth in urban population has resulted in the generation of huge quantities of wastewater worldwide (Singh & Agrawal, 2010). Wastewater treatment facilities are responsible for treating large volumes of domestic and industrial sewage containing human waste. The treatment goal is to produce effluents of high enough quality for discharge back into the environment. Sewage sludge is a byproduct of this process and necessitates proper disposal (Walters et al., 2010; Zuloaga et al., 2012). Safe disposal of sewage sludge is one of the major environmental concerns (Singh & Agrawal, 2010).

Historically, sewage sludge has been disposed of by incineration, landfilling or ocean disposal (Bridle & Skrypski-Mantele, 2000). Nowadays, the most widespread method for sewage sludge disposal has become agricultural application, since it is the most economical outlet for sludge compared to incineration and landfilling (Zuloaga et al., 2012; Li et al., 2013; Chen et al., 2014). The use of sewage sludge in agriculture is one of the major causes of environmental pollution (Nouri et al., 2008). Although, sewage sludge and its compost offers an opportunity to recycle plant nutrients and organic matter to soil for crop production stimulating biological activity (Rodríguez et al., 2012; Zuloaga et al., 2012; Li et al., 2013; Haiba et al., 2014), its usage as a fertilizer is limited due to a large number of toxic pollutants found in this matter (Lillenberg et al., 2010a; Lillenberg, 2011).

Composting is recognized as one of the most important recycling options for sewage sludge (Hara & Mino, 2008; Dorival-García et al., 2015). Since sewage sludge is mainly composted in Estonia and often re-used in agriculture as a fertilizer, several composting methods are applicable, but the selection of the method is dependent on the investment and operation cost, time required to reach compost stability and maturity, the availability of land, origin of raw materials and bulking agents (Ruggieri et al., 2008; Mollazadeh, 2014; Nei et al., 2014).

Several sludge composting experiences have been shared in Estonia (Kanal & Kuldkepp, 1993; Varnik et al., 2006; Kriipsalu et al., 2008; Kriipsalu & Nammari, 2010; Lillenberg et al., 2010a; Holm & Heinsoo, 2013; Kuusik et al., 2014; Menert et al., 2014). The most common sewage sludge composting methods are: static piles, aerated static piles, windrow and in-vessel systems (Yue et al., 2008). There are many factors that affect the composting process, such as the proportions of the mixture, temperature, rate of aeration, oxygen consumption rates, compost pile size, moisture content, pH and carbon-to-nitrogen ratio (Luo et al., 2008; Chen et al., 2014; Malinska et al., 2014; Nayak & Kalamdhad, 2014). Also, microorganisms play a key role in composting processes and nutrient turnover, and even slight changes in microbial activity and community composition due to antimicrobial agents may result in poor compost quality and prolonged time needed for compost stability (Nei et al., 2014). Respiration is a global measure of the total microbial activity that can provide a reliable, repeatable and scientifically sound assessment of microbial activity, respirometry (CO_2 evolution rate and/or O_2 uptake rate) has been widely used to evaluate microbial activity and composting efficiency (Liang et al., 2003; Barrena Gómez et al., 2006). The second widely used parameter for the evaluation of microbial activity is microbial biomass-C, measured by the substrate induced respiration based on Platen & Wirtz, 1999. Also, one of the methods of obtaining information about the dynamics of composting processes is the bacterial-to-fungal ratio (Joergensen & Wichern, 2008). The microbial community may reflect the evolution and performance of the composting process thus acting as an indicator of compost maturity (Nei et al., 2014; Wang et al., 2015).

Since sewage sludge has high moisture content it cannot be composted alone − in order to absorb moisture it should be mixed with dry materials, which act as bulking agent thereby improving the aeration and the compost quality (Nayak & Kalamdhad, 2014; Zhou et al., 2014). Sludge and bulking agent proportions in compost influence the composting reaction rate and the final compost quality. Sludge can be mixed with different bulking agents, sources of carbon, such as peat, straw, wood chips, leaves, ash, peat, sawdust (Komilis et al., 2011; Cukjati et al., 2012; Maulini-Duran et al., 2013; Malinska et al., 2014).

A range of studies has shown that some pharmaceuticals and personal care products (PPCPs) are neither completely removed by sewage treatment, nor completely degraded in the environment (Redshaw et al., 2008; Lillenberg et al., 2009; Lillenberg et al., 2010a; Jelic et al., 2011; Rodríguez-Rodríguez et al., 2012; Borgman & Chefetz, 2013; Haiba et al., 2013b; Narumiya et al., 2013; Reichel et al., 2013). Although, their concentrations are much lower than the levels of traditionally known organic pollutants, the potential long-term effects of these compounds to humans, plants and animals cannot be ignored (Lillenberg et al., 2009; Nei et al., 2014; Van Doorslaer et al., 2014; Prosser & Sibley, 2015; Bártíková et al., 2016).

FATE OF PHARMACEUTICAL RESIDUES DURING SEWAGE SLUDGE COMPOSTING

Pharmaceuticals have been used for decades to prevent and treat human and animal diseases (Zhang et al., 2008; Li et al., 2014). Recently, there has been increasing concern about the effects of pharmaceuticals in aquatic and terrestrial ecosystems, as they can affect the efficiency of microbial-mediated processes (the regeneration of nutrients, carbon and nitrogen circulation and digestion of pollutants) in the environment (Girardi et al., 2011; Jelic et al., 2011; Bergersen et al., 2012; Martín et al., 2012; Chen et al., 2013; Li et al., 2014).

As a result of regular industrial, agricultural and household activities, a variety of compounds enter into the environment, of which only a small percentage are studied for their toxicological effects on humans and the environment (Peysson & Vulliet, 2013). Approximately 4,000 drug substance is used in Europe (human and veterinary), of which may have responsive impact to the environment (Rodríguez-Rodríguez et al., 2011). About 150 medical compounds are studied that have been found in the environment, but mostly in water samples (Rivera-Utrilla et al., 2013; Li et al., 2014). For example, the Estonian Statistics on Medicines data show that over the years the proportion of consumption of different drugs has increased, both over-the-counter as well as prescription drugs (State Agency of Medicines, 2011; 2013). There is no reliable information of how many people actually do or do not consume their drugs, how many medicines are not administered and how many different compounds are thrown into the sewage system or to the garbage. The increasing proportions of administered drugs and personal care products is alarming because of the compound releases to the environment are not controlled (Motoyama et al., 2011; Gonzalez-Martinez et al., 2014), which involves a potential threat to the environment (Vasskog et al., 2009; Rodríguez-Rodríguez et al., 2011; Peysson & Vulliet, 2013).

A wide variety of pharmaceutically active compounds are present in wastewater effluents, surface waters, and ground waters (GWRC, 2008), and the sewage treatment plants are unable to remove all these substances. The removal rates of individual drugs during passage through a sewage treatment plant have varied from 12 to 90% (Stumpf et al., 1999; Butkovskyi et al., 2016). The fate of pharmaceuticals may be divided into three principal routes (Richardson & Bowron, 1985):

1. The substance is ultimately mineralized to carbon dioxide and water;
2. The substance is lipophilic and not readily degradable, so part of the substance will be retained in the sludge. These substances are able to contaminate soil if the sludge is dispersed onto fields;
3. The substance is metabolised to a more hydrophilic form of the parent lipophilic substance, but is still persistent and therefore will pass the sewage treatment plant, ends up in the receiving waters (rivers, seas) and may therefore affect the aquatic organisms, if the metabolites are biologically active.

Presence of different pharmaceuticals in sewage sludge is apparent, but there is still a lack of information concerning the fate of pharmaceutical residues in the environment (Kümmerer, 2008; Lillenberg, 2011). Pharmaceuticals are often not readily degradable (Richardson & Bowron, 1985; Gavalchin & Katz, 1994; Marengo et al., 1997; Halling-Sørensen et al., 2002; Hamscher et al., 2002; Carballa et al., 2004). Still, remarkable amounts of pharmaceuticals enter the soil via fertilizing with sewage sludge (Golet et al., 2002; Haiba et al., 2013a).

Medical substances have many necessary properties to bio-accumulate and provoke change in ecosystems (Kipper et al., 2010; Baran et al., 2011). No trigger values exist for drug residues in sewage sludge neither in Estonia (Decree of Estonian Minister of the Environment) nor in the European Union (EU Council Directive 86/278/EEC; Lillenberg et al., 2009). The most closely related act is the EU directive EMEA/CVMP/055 establishing trigger values for drug residues in manure (EMEA/CVMP/055/96). The content of drug residues should not exceed 100 μg kg^{-1} in manure and 10 μg kg^{-1} in the soil fertilized with manure. Montforts (2005) suggests that these figures should be remarkably lower. Soil organisms, microflora and plants are directly exposed to contaminants in sludge-amended soils.

The presence and content of some widely used pharmaceuticals was determined in sewage sludge and in its compost in the two Estonian largest cities, Tartu and Tallinn (Lillenberg, 2011). The sewage sludge in Tartu was treated by composting – mixing with tree bark (volume ratio 1:1). The methane fermentation and mixing with peat (volume ratio 1:0.75) were used in Tallinn. The samples were taken from anaerobically digested sludge (before mixing with peat) in Tallinn and from untreated sludge (before composting) in Tartu. The concentrations of most of the pharmaceuticals (ciprofloxacin-CIP, norfloxacin-NOR, ofloxacin-OFL, sulfadimethoxine-SDM and sulfamethoxazole-SMX) decreased significantly after sewage sludge digestion and compost processes, but many of them were still present in compost. The degradation of pharmaceutical residues was more efficient in Tallinn probably due to anaerobic sludge digestion (compost was made by mixing the treated sewage sludge with peat) compared to the results obtained in Tartu (raw sewage sludge was mixed with tree bark). The results of the relevant pilot studies are described in detail in Lillenberg et al. (2010a) and Lillenberg (2011).

Interestingly, SDM was present in most sludge and in some compost samples, although this antimicrobial was not marketed any more during the years of 2007 and 2008 in Estonia. It is possible that 'old' supplies were put to use or small amounts of this chemical were imported from other countries (Lillenberg et al., 2010a; Nei et al., 2010).

According to Lillenberg (2011) the highest concentrations of pharmaceuticals were found in Tallinn sewage sludge: CIP 1,520 µg kg^{-1} and NOR 580 µg kg^{-1} (dm). The highest detected concentration of CIP exceeded the trigger value for manure (100 µg kg^{-1}) over four times. The concentrations of OFL (134 µg kg^{-1}), SDM (73 µg kg^{-1}) and SMX (22 µg kg^{-1}) were lower (Table 1). The average contents of antibiotics were: CIP 737 µg kg^{-1}, NOR 279 µg kg^{-1}, OFL 80 µg kg^{-1}, SDM 2 µg kg^{-1} and SMX 18 µg kg^{-1} (dm). As a rule, the concentrations of pharmaceuticals in Tallinn sewage sludge from were relatively low. Still, in some cases the concentrations of CIP, NOR and OFL were over the trigger value (Table 1).

Table 1. The highest concentrations of pharmaceuticals detected from Tallinn sewage sludge, µg kg^{-1} (dm) (reproduced from Lillenberg, 2011)

Month	CIP	NOR	OFL	SDM	SMX
January	**1,520**	**580**	**134**	3	22
February	67	67	17	73	5
March	58	31	8	3	1
April	58	33	3	n.d.	2
May	**150**	**215**	7	0.4	n.d.
June	**206**	**163**	17	n.d.	4
July	39	37	4	n.d.	n.d.
August	11	26	5	n.d.	4
September	0.4	0.4	n.d.	n.d.	n.d.
November	42	16	9	3	3
December	53	85	37	4	7

CIP – ciprofloxacin; NOR – norfloxacin; OFL – ofloxacin; SDM – sulfadimethoxine; SMX – sulfamethoxazole; n.d. – not detected.

In Tartu, contrarily, the concentrations of CIP and NOR were in most cases over the trigger value, the high content of OFL was detected only in August, September and October (Lillenberg, 2011). The content of sulfonamides (SAs – SDM and SMX) was quite low in both cities, under the trigger value set for drug residues in manure (100 µg kg^{-1}) (Tables 1, 2). In Tartu at least one of SAs was present in every sludge sample (Table 2). The contents of SMX were in the range of 0.0–22 µg kg^{-1}, and SDM 0.00–73 µg kg^{-1} (dm) in Tallinn. In Tartu contents of SMX were between 0.0–11 µg kg^{-1}, and SDM 0.0–32 µg kg^{-1} (dm). The highest concentrations of antimicrobials in sewage sludge from Tartu were: NOR – 439 µg kg^{-1} and CIP – 442 µg kg^{-1} (dm). OFL was present in every sludge sample from Tartu and the highest concentration was 157 µg kg^{-1} (dm) (Table 2).

Table 2. The highest concentrations of pharmaceuticals determined from Tartu sewage sludge, μg kg^{-1} (dm) (reproduced from Lillenberg, 2011)

Month	CIP	NOR	OFL	SDM	SMX
January	**315**	82	86	8	6
February	**423**	**263**	68	32	7
March	89	60	26	0.4	1
May	**174**	**264**	22	1	n.d.
June	**265**	**264**	47	n.d.	16
July	67	**104**	19	n.d.	6
August	**442**	**439**	**111**	24	n.d.
September	**231**	**188**	**157**	22	9
October	**259**	**126**	**149**	4	n.d.
November	**134**	**105**	33	6	11
December	71	40	32	9	6

CIP – ciprofloxacin; NOR – norfloxacin; OFL – ofloxacin; SDM – sulfadimethoxine; SMX – sulfamethoxazole; n.d. – not detected.

The degradation of pharmaceuticals was more efficient in the case of composting in Tallinn. During 12 months composting period the concentrations of all the studied pharmaceuticals diminished for 99.9%, whereas in Tartu this indicator showed the value on average 90 ± 4%. The only exception was SDM, which 'disappeared' fully in both cases. In Tallinn the anaerobically digested sludge was mixed with peat and composted. In Tartu raw sewage sludge was mixed with tree bark (1:1) and settled in piles. The media vas mixed at least twice per month during eight-months period. It has been shown, that a higher decrease of pharmaceuticals is observed after anaerobic digestion than after aerobic digestion, which can be explained by a higher degradation under anaerobic conditions (Martin et al., 2015).

The degradation rate of pharmaceutical residues is dependent on the initial components of the compost. Fine sawdust appears to be an excellent sewage sludge amendment: from the agricultural point of view, sludge co-composted with particularly fine-textured sawdust is claimed to be an excellent compost material to be applied to soils (Ammari et al., 2012; Nei et al., 2015). Kim et al. (2012) have shown that sawdust is able to initiate efficient composting, leading to elevated composting temperatures, and consequently resulting in the reduction of residual concentrations of pharmaceuticals to reasonable levels in a relatively short composting period.

According to Haiba et al. (2013b), composting remarkably reduces the concentrations of these pharmaceuticals. In most experiments their concentrations decreased by 95% or more during 4 months of composting (Table 3). The best results were obtained when the sludge was mixed with sawdust. In the case of using straw or peat instead the decomposition rates were lower. Additions of sawdust clearly speeded up this process, whereas the mixtures with peat and straw performed lower abilities to decompose pharmaceutical residues. No clear evidence was received concerning the impact of oil shale amendments on the degradation speed of the studied pharmaceuticals. Many studies have shown that sawdust has been proven to be a good bulking agent for sewage sludge composting (Banegas et al., 2007; Zorpas & Loizidou, 2008; Haiba et al., 2013a & 2013 b). The decline of tetracycline and sulfonamide concentrations was highly dependent on the presence of sawdust while there was no influence of sawdust on tylosin decline (Kim et al., 2012).

Table 3. Degradation of pharmaceuticals in sewage sludge compost mixtures during 4-months composting period, %

Bulking agent (% from dry matter)	**SMX**	**SDM**	**NOR**	**CIP**	**OFL**
1. peat (50)	83	77	90	92	100
2. sawdust (33)	100	99	96	95	100
3. sawdust + oil shale ash (29+14)	100	96	82	94	99
4. sawdust + wood chips (total 43)	100	99	91	98	86
5. straw (50)	99	98	79	90	74

CIP – ciprofloxacin; NOR – norfloxacin; OFL – ofloxacin; SDM – sulfadimethoxine; SMX – sulfamethoxazole.

PHARMACEUTICALS AND PLANT UPTAKE

The significance of the route involving the uptake of several medicines from soil by plants in terms of risk to human health is evident (Lillenberg et al., 2010b; Prosser & Sibley, 2015; Wu et al., 2015). As the compost made from sewage sludge contains detectable amounts of pharmaceutical residues, experiments were conducted to study the significance of their uptake into plants from soil under 'real' conditions. Therefore, experiments were performed to investigate the potential accumulation of the studied pharmaceuticals – fluoroquinolones (FQs) and sulfonamides (SAs) – taken up by food plants (namely – carrot, potato, lettuce, wheat) from the soil fertilized with sewage sludge or its compost. The results of these experiments are shown in Lillenberg et al. (2010a; 2010b), Kipper et al. (2010) and Nei et al. (2010).

The uptake of pharmaceuticals by the studied food plants was noticeable. It has been shown that due to the low adsorption of SAs on soil particles they readily migrate into plants (Haiba et al., 2013a). Different behaviour is characteristic to FQs due to their sorption to sewage sludge and soil particles (Golet et al., 2003). Therefore, as a rule, the content of SAs in the plants was higher. The content of the studied pharmaceuticals was higher in plats cultivated in sandy soil (Lillenberg, 2011). In loamy soil the molecules of both SAs and FQs attach to clay particles reducing their uptake by plants. Fig. 1 is to illustrate the said. The amounts of FQs going into potato do not depend much on soil type. The application of sewage sludge compost as a fertilizer and the following uptake of pharmaceuticals by food plants may cause contamination of these plants (Haiba et al., 2013a).

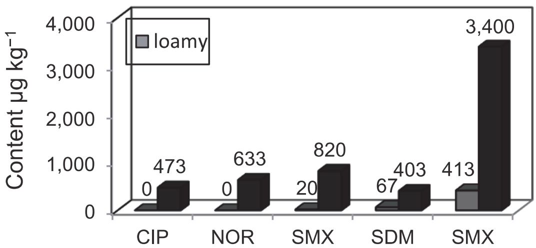

Figure 1. Average concentrations of pharmaceuticals in carrot roots grown in different soils at drug concentration of 10 mg kg^{-1}: CIP – ciprofloxacin; NOR – norfloxacin; OFL – ofloxacin; SDM – sulfadimethoxine; SMX – sulfamethoxazole.

Toxic compounds entering into the soil may affect microbial activity, plant growth and development and may have adverse effects on living organisms (Lillenberg et al., 2010b; Michelini et al., 2012; Haiba et al., 2013a; Nei et al., 2014). Further studies concerning the plant uptake of a wide spectrum of commonly used pharmaceuticals from soils fertilized with sewage sludge or its compost are needed to ensure food safety.

Lillenberg concludes in her PhD thesis (Lillenberg, 2011) that the residues of pharmaceuticals readily accumulate in several food plants. This phenomenon remarkably depends on the nature and concentration of a pharmaceutical and soil type. When using the sewage sludge compost as a fertilizer, it should be carefully tested for the safety. The content of pharmaceuticals in the compost made from sewage sludge may easily lead to the elevated concentrations in food plants if the compost is used as a fertilizer. Still, wheat grains had low or zero concentrations of the analysed pharmaceuticals. This confirmed the potential applicability of sewage sludge compost for fertilization of the crops of this type (Haiba et al., 2013a). Further work should be conducted to determine different types of pharmaceuticals and other organic pollutants by food plants (Lillenberg, 2011). It is evident that the development of novel sewage sludge treatment technologies are needed to solve environmental problems related to sewage sludge exploitation.

PUBLICATIONS AND THESES

Vermicomposting

Vermicomposting technology is a simple and environmentally friendly biological treatment of wastes. As a result of the work published in Ivask et al. (2013) and Haiba et al. (2014) the applicability and efficiency of using earthworms *Eisenia fetida* and *Dendrobaena veneta* in vermicomposting of sewage sludge and household organic residues in the countries with the climate comparable to Estonia was demonstrated.

Compost in afforestation

In Estonia the reforestation of depleted peat and sand mining areas is often complicated due to the unfavourable physical, chemical and biological properties of soils. The impact of artificial roots and soil amelioration with green waste compost in the afforestation of depleted peat fields and sand pits was studied. The results of this work is presented in Jarvis et al. (2012) and Jarvis et al. (2016). Added compost caused significantly improved height growth of the studies tree species seedlings, hence enhanced the growth conditions locally.

Development of novel methodologies for the determination of pharmaceutical residues

Novel approaches for the quantitative determination of traces of commonly used pharmaceuticals in sewage sludge and plants were developed (Lillenberg et al., 2009; Kipper et al., 2011; Kipper, 2012). The compounds were simultaneously extracted from sewage sludge by pressurized liquid extraction (PLE). A novel and effective method for PLE was developed. Solid-phase extraction was used for cleaning up the extracts.

Dissertations defended

PhD thesis: Karin Kipper, Fluoroalcohols as Components of LC-ESI-MS Eluents: Usage and Applications, 2012. A novel and efficient methodology for pharmaceutical analyses in complex matrices (e.g. blood plasma and environmental samples) was developed and tested.

PhD thesis: Merike Lillenberg, Residues of some pharmaceuticals in sewage sludge in Estonia, their stability in the environment and accumulation into food plants via fertilizing, 2011. The aim of the work was to study the presence of some widely used pharmaceuticals in Estonian sewage sludge and its compost and the uptake of these pharmaceuticals from fertilized soils by some food plants. As a result of this research the following was established:

1. Pharmaceuticals were present in sewage sludge and its compost from both Tallinn and Tartu and in several samples their concentrations exceeded the relevant trigger values for manure.
2. Degradation of pharmaceuticals took place as a result of composting.
3. The main reason of the decrease in pharmaceutical concentrations during composting was the applied sludge treatment technology.
4. The uptake of the studied pharmaceuticals by food plants was obvious. The application of sewage sludge compost as a fertilizer and the resulting uptake of pharmaceuticals by food plants may cause contamination of these plants.

CONCLUSIONS

Land application of composts is an important and efficient tool in the remediation of industrial landscapes and agricultural soils in Estonia. Still, due to the frequent presence of different undesired residues, composts made from sewage sludge need careful inspection before their use. The work should be continued by the development of novel and more efficient composting technologies, leading to intelligent solutions of environmental problems related to biowaste exploitation.

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Appendix 4

Paper IV

Jüri Järvis; Mari Ivask; Lembit Nei; Annely Kuu; Egge Haiba (2017). Afforestation of Cutover Peatland with Spot Application of Sewage Sludge Compost. Baltic Forestry, 23 (3), 644−657.

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

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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.

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.

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.

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.

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

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

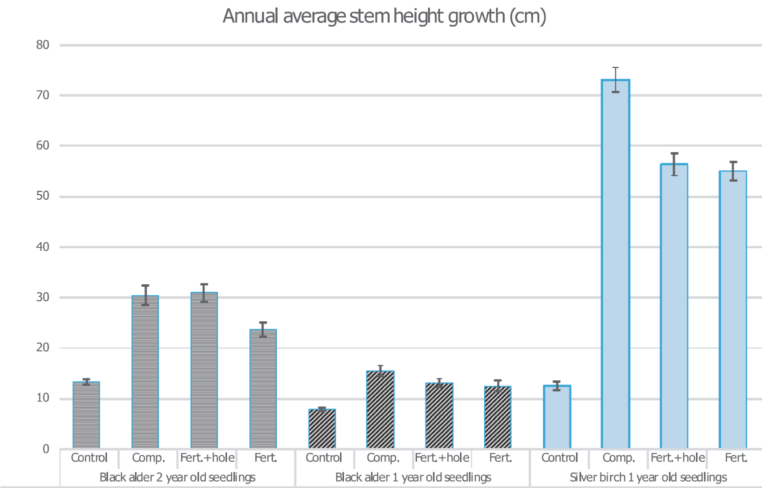
Roots' annual growth was calculated by subtracting average initial root length at the time of planting from final root length. The average initial root lengths were 10 cm in the vertical and horizontal direction for all seedlings, except for the one-year-old black alder seedlings, which measured 5 cm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

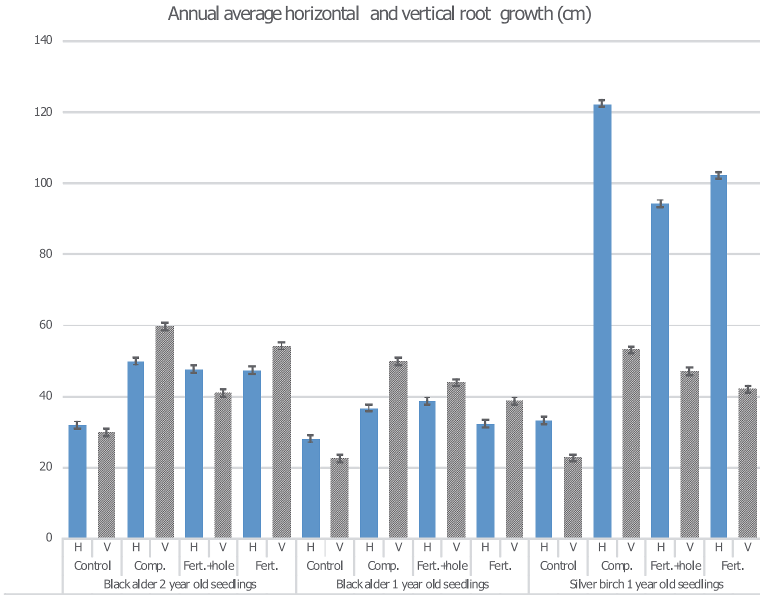
In the current work, in most cases (96%) neither sewage compost fillings nor the spot-applied fertiliser caused weed growth around the seedlings. In 2% of the cases the weeds grew high enough to create competition for light with the tree seedlings (they were as high or higher as the seedlings). All the 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,



	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.	
	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V
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.

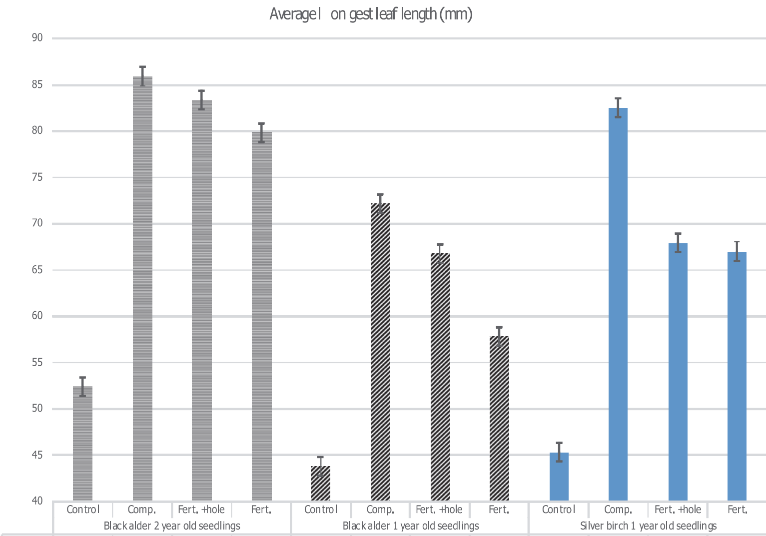
Discussion and conclusions

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

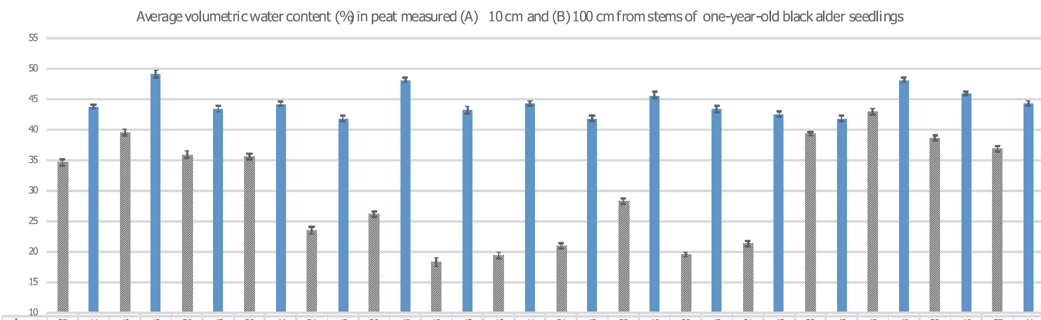
Figure 4. Comparison of the average longest leaf lengths (mm). **SE** denotes standard errors of average longest leaf (mm), error bars on graph represent standard errors; **Number** denotes the number of leaves measured

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.

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Curriculum vitae

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Education

2010–2012 Tallinn University of Technology, PhD studies
1998–2003 Estonian Agricultural University, PhD studies
1995–1997 Estonian Agricultural University, MSC
1991–1995 Estonian Agricultural University, BSC
1987–1991 Kaarepere Higher Forestry School (cum laude)

Language competence

Estonian – mother tongue
English – fluent
Finnish – average
Russian – basic skills

Professional employment

1997–… Consulting company OÜ Formaks, owner
2012–2012 Tallinn University of Technology, Tartu College, Lecturer (0.10)
2007–2007 Tallinn University of Technology, Tartu College, Lecturer (0.30)
2005–31.08.2009 Estonian University of Life Sciences, Institute of Forestry and Rural Engineering, Lecturer (0.50)
2002–2005 Estonian Agricultural University / Estonian University of Life Sciences, Institute of Forest Management / Institute of Forestry and Rural Engineering, Lecturer (1.00)
2000–2001 Estonian Agricultural University, Institute of Forest Management, Researcher (1.00)
1998–2000 Estonian Agricultural University, Institute of Forest Management, Lecturer (0.50)
1996–1997 Estonian Agricultural University, Institute of Forest Management, Researcher (0.75)
1995–1996 Estonian Agricultural University, Institute of Forest Management, Contract (1.00)

R&D related managerial and administrative work

2004−2009 Participation as an authorized representative (on behalf of Estonian Agricultural University) in cooperation project “Improvement of timber measurement practice” Estonian Private Forest Union, Estonian Forest and Wood Industries Association, State Forest Management Centre, Estonian Agricultural University / Estonian University of Life Sciences and Ministry of Environment
2002−2003 Participation in project “Improvement in timber measurement practice” as an expert according to contract with Foundation Private Forest

Centre in cooperation with Finnish The Central Union of Agricultural Producers and Forest Owners (MTK), Maa- ja metsätaloustuottajain Keskusliitto MTK

1999−1999 Working out Contract examples for forestry operations according to contract with Foundation Private Forest Centre

Creative work

Consultation work since 2014 for start-up company "Timbeter" for picture analyzing software development for automatic roundwood volume estimation from photos taken with mobile device.

Utility models on orientation belt (EE 00876 U1), using pneumatic hand-gun for forest seeding (EE 00893 U1), producing seed granules with continuous process (EE 01035 U1), seed bearer-marker (EE 01057 U1), automatic plant watering device (EE 01149 U1).

Additional career information

Honours & awards

1997, Jüri Järvis, II award by Estonian Science Fund, Commission of Agricultural Sciences

Name changes

Estonian Agricultural University was renamed to Estonian University of Life Sciences in 2005.

Personal family name was changed from Jänes to Järvis. [Directive of Minister of Regional Affairs No 68. 07 September 2009 "Uue eesnime, perekonnanime või isikunime andmine"] (in Estonian)

Academic degrees

Master's Degree, 1997, (supervisor) Mart Vaus, Ümarpuidu mahu määramise võimalustest (Possibilities for Estimation of Roundwood Volume), Estonian Agricultural University, Tartu, Estonia.

Field of research

Biosciences and Environment; Forest Sciences; Specialities: development of forest and roundwood volume estimation methods; afforestation solutions; recultivation of abandoned mining areas.

Participation in project

ETF9258 Mesofauna impact on the decomposition processes for soil quality, their significance in the food chain and succession on human affected areas (1.01.2012−31.12.2016), Principal investigator: Annely Kuu, Tallinn University of Technology , Tartu College of TUT

Supervised dissertations

P. Kiivramees, Master's Degree, 2010, (sup) Jüri Järvis, Digitaalfotodelt virnastatud ümarpuidu mahu määramise täpsusest ja efektiivsusest. [Accuracy and effectiveness of roundwood volume assesment from digital photos], (in Estonian), Estonian University of Life Sciences.

Publications

1. Jüri Järvis; Mari Ivask; Lembit Nei; Annely Kuu; Egge Haiba (2017). Afforestation of Cutover peatland with Spot Application of Sewage Sludge Compost. Baltic Forestry 23 (3): 644-657.
2. Egge Haiba; Lembit Nei; Mari Ivask; Jane Peda; Jüri Järvis; Merike Lillenberg; Karin Kipper; Koit Herodes. (2016). Sewage sludge composting and fate of pharmaceutical residues – recent studies in Estonia. Agronomy Research, 14 (5), 1583−1600.
3. Jüri Järvis; Mari Ivask; Lembit Nei; Annely Kuu; Aarne Luud (2016). Effect of Green Waste Compost Application on Afforestation Success. Baltic Forestry, 22 (1), 90−97.
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11. Jänes, Jüri; Padari, Allar (2004). Metsa hindamine. Halo Kirjastus.
12. Jänes, J.; Lang, M. (2003). Joonproovide kasutamise võimalustest virnatäiuse koefitsiendi määramisel. Külliki Kiviste. EPMÜ Metsandusteaduskonna toimetised (98−106). Eesti Põllumajandusülikooli Metsandusteaduskond.
13. Lang, M.; Jänes, J. (2003). Virnatäiuse koefitsiendi hindamine digitaalkaamera piltidelt klassifitseerimitehnika abil. Külliki Kiviste. EPMÜ Metsandusteaduskonna toimetised (107−115). Eesti Põllumajandusülikooli Metsandusteaduskond.
14. Jänes, Jüri (2003). Metsa ja puidu mõõtmise uusi kontrollvõimalusi. Eesti Mets, 2, 28−34.
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17. Jänes, Jüri (2000). Ümarpuidu mõõtmine ja hindamine. Kaupo Ilmet (Toim.). Metsamehe kalender-käsiraamat (155−229). Põltsamaa: VALI trükikoda.
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20. Jänes, Jüri (1997). Ümarpuidu mahu määramise võimalustest. (Eesti Põllumajandusülikool). Tartu: Eesti Põllumajandusülikool.
21. Jänes, J. 1997. Uus ümarmetsamaterjalide mõõtmise juhend. *Eesti mets* nr 10 (60) oktoober.
22. Uus, Andres; Jänes, Jüri (1997). Requirements on quality and measurement of roundwood. Tartu: Tõravere trükikoda.
23. Uus, Andres; Jänes, Jüri (1997). Ümarmetsamaterjalide kvaliteedi ja mõõtmise nõuded. Tartu: Tõravere trükikoda.

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Isikuandmed

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Hariduskäik

2010–2012 Tallinna Tehnikaülikooli Säästva Tehnoloogia Instituut, täiendav doktoriõpe

1998–2003 Eesti Põllumajandusülikool, Metsandusteaduskond, doktoriõpe metsamajanduse erialal

1995–1997 Eesti Põllumajandusülikool, Metsandusteaduskond, magistriõpe metsakorralduse erialal, MSC

1991–1995 Eesti Põllumajandusülikool, Metsandusteaduskond, metsakorralduse eriala, BSC

1987–1991 Kaarepere sovhoostehnikum, Kesk-eriharidus (lõpetatud kiitusega)

Keeleoskus

Eesti keel – emakeel

Inglise keel – väga hea

Soome keel – keskmine

Vene keel – põhioskused

Teenistuskäik

1997–… Konsultatsioonifirma OÜ Formaks, omanik

2012–2012 Tallinna Tehnikaülikool, Tartu Kolledž, lektor (0,10)

2007–2007 Tallinna Tehnikaülikool, Tartu Kolledž, lektor (0,30)

2005–31.08.2009 Eesti Maaülikool, metsandus- ja maaehitusinstituut, lektor (0,50)

2002–2005 Eesti Põllumajandusülikool, metsandusteaduskonna metsakorralduse instituut, lektor (1,00)

2000–2001 Eesti Põllumajandusülikool, metsandusteaduskonna metsakorralduse instituut, teadur (1,00)

1998–2000 Eesti Põllumajandusülikool, metsandusteaduskonna metsakorralduse instituut, lektor (0,50)

1996–1997 Eesti Põllumajandusülikool, metsandusteaduskonna metsakorralduse instituut, teadur (0,75)

1995–1996 Eesti Põllumajandusülikool, lepinguline uurimistöö Eesti Metsaametile teemal "Kase, kuuse ja männi paberipuude mahu määramine tiheduse ja niiskuse alusel" (1,00)

Teadusorganisatsiooniline ja -administratiivne tegevus

2004−2009 Eesti Põllumajandusülikooli volitatud esindajana osalemine Eesti Erametsa Liidu, Eesti Metsatööstuse Liidu, Riigimetsa Majandamise Keskuse, Eesti Põllumajandusülikooli ja Keskkonnaministeeriumi koostööprojektis „Puidu mõõtmispraktika parandamine"

2002−2003 Projektis „Puidu mõõtmispraktika parandamine Eestis“ eksperdina osalemine. Osalemine toimus Sihtasutus Erametsakeskus sõlmitud lepingu alusel, koostöös Soome Maa- ja Metsaomanike Keskliiduga.

1999−1999 Metsamajanduslike tööde lepingute väljatöötamine sihtasutuse Erametsakeskus lepingu alusel

Loometöö

Konsultatsioonitöö idufirmale "Timbeter" pildianalüüsil põhineva tarkvara väljaarendamisel ümarpuidu mahu määramise automaatse meetodi tarbeks mobiilseadmetele (alates 2014. aastast).

Registreeritud kasulikud mudelid "Orienteerumisvöö" (EE 00876 U1), "Pneumaatilise käsirelva metsakülvil kasutamine" (EE 00893 U1), "Seade seemnegraanulite pressimiseks pideva protsessiga" (EE 01035 U1), "Seemnekandja-marker" (EE 01057 U1), "Automaatne taimekastmisseade" (EE 01149 U1).

Täiendav info

Teaduspreemia

1997. aastal Eesti Teadusfondi põllumajandusteaduste ekspertkomisjoni II preemia

Nimemuutused

Aastal 2005 nimetati Eesti Põllumajandusülikool ümber Eesti Maaülikooliks.

Aastal 2009 võttis autor uue perekonnanime "Järvis" vastavalt Regionaalministri 07. Septembri 2009. käskkirjale nr 68 "Uue eesnime, perekonnanime või isikunime andmine".

Teaduskraad

Magistrikraad (teaduskraad), 1997, (juhendaja) Mart Vaus, Ümarpuidu mahu määramise võimalustest, Eesti Põllumajandusülikool, Tartu, Eesti.

Teadustöö põhisuunad

Bio- ja keskkonnateadused ning metsandusteadus. Põhisuunad: metsa ja puidu mahu ja kvaliteedi määramisvõimaluste arendamine, säästev metsamajandus, ammendatud karjääride rekultiveerimine.

Projektides osalemine

ETF9258 "Mesofauna mõju läbi lagunemisprotsesside mulla kvaliteedile, nende olulisus toiduahelas ja suktsessioon inimese poolt mõjutatud piirkondades (1.01.2012−31.12.2016)", Annely Kuu, Tallinna Tehnikaülikool, TTÜ Tartu Kolledž.

Juhendatud väitekirjad

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Publikatsioonid

1. Jüri Järvis; Mari Ivask; Lembit Nei; Annely Kuu; Egge Haiba (2017). Afforestation of Cutover peatland with Spot Application of Sewage Sludge Compost. Baltic Forestry, 23 (3), 644−657.
2. Egge Haiba; Lembit Nei; Mari Ivask; Jane Peda; Jüri Järvis; Merike Lillenberg; Karin Kipper; Koit Herodes. (2016). Sewage sludge composting and fate of pharmaceutical residues – recent studies in Estonia. Agronomy Research, 14 (5), 1583−1600.

3. Jüri Järvis; Mari Ivask; Lembit Nei; Annely Kuu; Aarne Luud (2016). Effect of Green Waste Compost Application on Afforestation Success. Baltic Forestry, 22 (1), 90−97.
4. Järvis, Jüri (2013). Forest Measurement with Relascope. Practical description for fieldwork with examples for Estonia.
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9. Jänes, Jüri (2006). Presenting an idea: log-by-log real-time data transmission from harvester to server over GPRS. Metsanduslikud uurimused = Forestry studies, 45, 177−181.
10. Jänes, Jüri (2006). Metsa relaskoopmõõtmine. Tartu: Halo Kirjastus.
11. Jänes, Jüri; Padari, Allar (2004). Metsa hindamine. Halo Kirjastus.
12. Jänes, J.; Lang, M. (2003). Joonproovide kasutamise võimalustest virnatäiuse koefitsiendi määramisel. Külliki Kiviste. EPMÜ Metsandusteaduskonna toimetised (98−106). Eesti Põllumajandusülikooli Metsandusteaduskond.
13. Lang, M.; Jänes, J. (2003). Virnatäiuse koefitsiendi hindamine digitaalkaamera piltidelt klassifitseerimitehnika abil. Külliki Kiviste. EPMÜ Metsandusteaduskonna toimetised (107−115). Eesti Põllumajandusülikooli Metsandusteaduskond.
14. Jänes, Jüri (2003). Metsa ja puidu mõõtmise uusi kontrollvõimalusi. Eesti Mets, 2, 28−34.
15. Jänes, Jüri (2001). Calculation of Roundwood Volume Through its Density. Baltic Forestry, 7 (2), 57−62.
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18. Uus, Andres; Jänes, Jüri (1998). Ümarmetsamaterjalide kvaliteedi ja mõõtmise nõuded ning mahutabelid. Abiks metsaomanikule (6−89). Tallinn: Kommunaalprojekt trükikoda.
19. Jänes, Jüri (1997). Virnmaterjalide mõõtmise hetkeseis Eestis ja võimalik areng. EPMÜ teadustööde kogumik. Metsandus, 189, 217−219.
20. Jänes, Jüri (1997). Ümarpuidu mahu määramise võimalustest. (Eesti Põllumajandusülikool). Tartu: Eesti Põllumajandusülikool.
21. Jänes, J. 1997. Uus ümarmetsamaterjalide mõõtmise juhend. *Eesti mets* nr 10 (60) oktoober.
22. Uus, Andres; Jänes, Jüri (1997). Requirements on quality and measurement of roundwood. Tartu: Tõravere trükikoda.
23. Uus, Andres; Jänes, Jüri (1997). Ümarmetsamaterjalide kvaliteedi ja mõõtmise nõuded. Tartu: Tõravere trükikoda.