Ecological Engineering 108 (2017) 296–306

Contents lists available at ScienceDirect

Ecological Engineering

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

Research Paper

The effect of oil shale ash and mixtures of wood ash and oil shale ash on the above- and belowground biomass formation of Silver birch and Scots pine seedlings on a cutaway peatland

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ARTICLE INFO

Keywords:
Biomass production
Wood ash
Oil shale ash
Betula pendula
Pinus sylvestris

ABSTRACT

Use of biofuel ashes for the afforestation of cutaway peatlands helps to balance the content of nutrients in peat substrate, which improves the survival of planted seedlings and increases significantly bio-production. The purpose of this study was to investigate the effect of fertilization with alkaline ashes on the above- and belowground biomass formation of four-year-old Silver birch (*Betula pendula* Roth) and five-year-old Scots pine (*Pinus sylvestris* L.) stands on a cutaway peatland. Five treatments were established: three mixtures with different proportions of wood ash (10–15 t ha^{-1}) and oil shale ash (10–15 t ha^{-1}), pure oil shale ash (10 t ha^{-1}) and control (unfertilized plot). Three years after fertilization with ashes the content of phosphorus was up to 150 times and that of potassium 23 times higher in the peat substrate treated with ashes than on the control plot. The growth and biomass formation varied among treatments and depends strongly on the content of P and K in the growth substrate. The best results were observed on plots of Silver birch treated with mixed ashes; there the seedlings annual height increment was 2–3 times (first year), 5–7 times (second year) and 8–9 times (third year) greater than on the control plot. The effect of mixed ashes on the annual height increment of Scots pine was weaker: the annual height increment was 1.4 times (first year), 3 times (second year) and 5 times (third year) greater than on the control plot. The effect of pure oil shale ash on the growth and biomass formation of trees was the smallest. The greatest root collar diameter increment of birch and pine was observed on the third vegetation period. Roots formed the largest part of the total Silver birch biomass, followed by stem, branches and leaves. At the end of the third year after treatment the largest part of the biomass of Scots pine was allocated to the needles, followed by roots, stem and branches. The biomass and biomass production were the greatest on the plots treated with mixed ashes, especially on the WA15 + OSA10 and WA15 + OSA10 treatments. The total bio-productivity of birch was until 4 times intense than in the case of pine. The average current annual biomass production of Silver birch and Scots pine stands were respectively 0.17–0.21 t ha^{-1} and 0.3–0.56 t ha^{-1} (mixed ashes), 0.04 t ha^{-1} and 0.16 t ha^{-1} (OSA10) and 0.02 t ha^{-1} (control).

1. Introduction

Estonian kukersite oil shale is the largest industrially exploited oil shale resource in the world (Teedumäe and Raukas, 2006). In 2009–2012 the volume of oil shale production did not change remarkably but in 2013 the production increased by more than 9% and totalled 20.5 million tonnes. The bulk of the extracted oil shale is consumed by power plants. In 2013 the consumption by power plants increased by 16.4%, whereas 85% of the electricity in Estonia was produced from oil shale (Statistics Estonia, 2014). In Estonia more than 85% of the total waste emerged from industries in 2007–2011 and 79% was produced in the oil shale and electric power industries. The bulk of oil shale ash is deposited in ash fields (Kuusik et al., 2012), only a small percentage of ash finds its way to secondary use (Ahmaruzzaman, 2010; Külaots et al., 2010; Shawabkeh, 2009; Smadi and Haddad, 2003; Trikkel et al., 2008; Vassilev et al., 2013; Wang and Wu, 2006; Wang et al., 2014). After the burning of oil shale during the process of electricity generation in Estonian power plants a large amount of oil shale ash is produced, annually approximately 6–7 million tonnes, of which only 3–6% is reused (Kuusik et al., 2012).

Today many industrialized countries put increased emphasis on the use of renewable energy sources, including biomass combustion for

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http://dx.doi.org/10.1016/j.ecoleng.2017.09.002
Received 25 April 2017; Received in revised form 19 August 2017; Accepted 5 September 2017
Available online 13 September 2017
0925-8574/

heat and electricity production (Jones et al., 2014). Wood ash is a by-product generated by burning wood and forest residues in thermal and electric power plants, chipboard and paper mills. The production of wood ash, which is already rather high in some forest areas, will increase in the near future as a result of the promotion of biomass fuel (Omil et al., 2007). The amount of wood ash in Estonia has been growing from year to year and will increase in the near future up to 35 000 t a year (Pitk et al., 2016). Some of the topical open questions related to extensive biomass combustion are what we are going to do with this huge amount of wood ash and if there are any environmental risks related (Vassilev et al., 2013).

Properties of biomass-based fuel and combustion tests showed that biomass is a promising renewable energy source and adding it to oil shale, the main local fuel in Estonia, could make the production of electricity from fossil oil shale more environmentally friendly and reduce the CO_2 emission from power plants (Kask et al., 2011). The use of low-quality wood for electricity production has reduced the impact of emissions on the environment: in 2011 the use of renewable biofuels decreased CO_2 emissions by 350 000–380 000 t and the amount of oil shale ash used for energy production decreased by 180 000 t (Eesti Energia, 2012). Therefore it is probable that in the future most of the ashes coming from power plants are mixtures of oil shale ash and wood ash. It is important to find possibilities for stimulating of wood biomass formation (especially formation of stems and shoots) by using nutrient-rich ashes.

Oil shale ashes are rich in calcium, magnesium, potassium and sulphur but contain only small amounts of phosphorus and some micronutrients like boron, copper, manganese, zinc etc. (Kärblane, 1996). The most common mineral ingredients of agricultural importance in oil shale ash are CaO (30–44%) as a liming agent, SiO_2 (27–32%), K_2O (2.7–7.0%) as a fertilizer and Fe_2O_3 (5.2–5.5%) (Saether et al., 2004). However, oil shale ashes also contain many trace elements (Pets et al., 1985; Häsänen et al., 1997). Although in most cases oil shale ash is not rich in trace elements, the concentrations of strontium, bromine and barium are rather high (Kuusik et al., 2012). Oil shale on the dry basis consists of three components relevant for combustion characteristics: the organic part, carbonates and sandy-clay minerals; the organic part includes kerogens and bitumen (Holopainen, 1991). Compared to other oil shales explored in the world, the organic content of the Estonian oil shale is rather high (~30%), from 1 t of Estonian oil shale 850 kWh of electricity can be produced (European Academies Science Advisory Council, 2007). In electric power plants, the amount of ash that remains after combustion is approximately 45–48% of oil shale dry mass (Bauert and Kattai, 1997).

The chemical composition of different wood ashes can vary a lot as it mostly depends on raw material composition, tree species (hardwood ash contains more K and P than softwood but less Ca and Si), boiler type, heating temperature, combustion technology and possible sources of contamination (Pärn et al., 2010; Pitman, 2006; van Loo and Koppejan, 2008). The content of N in ashes is low because it volatilizes during the combustion process. The chemical composition of wood ash varies; it generally contains Ca (120–249 g kg^{-1}), K (30–74 g kg^{-1}), P (6–17 g kg^{-1}) and Mg (12–33 g kg^{-1}) (Bramryd and Fransman, 1995; Hytönen, 2003; Pärn et al., 2009, 2010; Silfverberg, 1996; Steenari et al., 1999a). Wood ash contains all the elements required for plant growth, although only trace amounts of N (Demeyer et al., 2001; Vance, 1996). Scandinavian experience has proved its beneficial effect for tree growth on drained peatlands, where elements that limit plant growth are P and K (Ernfors et al., 2010; Moilanen et al., 2005; Väätäinen et al., 2011). Wood ash application increases the alkalinity and nutritional status of the soil (Brais et al., 2015; Huotari et al., 2015; Kikamägi et al., 2014; Ozolinčius et al., 2007).

Peatlands in Estonia cover up to 22.3% of the territory (Paal and Leibak, 2011). Estonia has a long history of peat extraction and about 1% of all peatlands are considered abandoned peat production areas (Orru and Orru, 2003). The post-harvesting area is a harsh environment for plants due to the unstable water conditions, wind erosion and frost heaving, which impede the establishment of plant cover during several decades (Lavoie et al., 2005; Price et al., 2003). Cutaway peatlands are characterized by variable peat thickness, low pH, high nitrogen contents and low phosphorus and potassium contents (Huotari et al., 2011; gi et al., 2014; Moilanen et al., 2005; , 2015).

In previous studies attention has been usually focused on the impact of fly oil shale ash as air pollution emitted from power plants (Liblik and Pensa, 2001; Vaasma et al., 2017) but the effect of oil shale ash as fertilizer on the growth of trees is widely known (Terasmaa and Pikk, 1995; Mandre et al., 1999; Ots et al., 2000). Forest scientists have focused at the influence of wood ash on the functioning of trees and the whole forest ecosystem but effect of mixed ashes (wood ash mixed with other nutrient-rich ashes) has been modestly investigated. Liming with powdered oil-shale ash in a heavily damaged forest ecosystems improved the health status of Scots pine stand (Terasmaa and Sepp, 1994; Terasmaa and Pikk, 1995). Oil shale ash is relatively poor in P (Kärblane, 1996), this may be the reason why Seemen et al. (2000) observed that trees fertilized with oil shale ash (20–25 t ha^{-1}) were smaller compared to control trees. A mixture with P-rich wood ash could be an alternative to promote the growth of trees in cutaway peatlands. Earlier studies show that treating peat with mixed wood ash and oil shale ash stimulates more biomass formation of Silver birch and Scots pine than treating with wood ash (Kikamägi and Ots, 2010; Kikamägi et al., 2013, 2014; Aguraijuja et al., 2015). A recent study showed a significant effect of mixed ashes (wood ash + oil shale ash) on the growth of trees (Kikamägi et al., 2014). Addition of nutrient-rich ashes increases notably the increment of whole aboveground biomass of trees, especially important is stimulating the formation of stems and shoots in point of using that kind of wood in bioenergy. Current study gives us new knowledge about stimulation of biomass formation with larger amounts and new proportions of wood ash and oil shale ash compared to earlier studies (Kikamägi et al., 2014).

It is important to develop environmentally safe, resource saving and sustainable techniques for recycling of wood ash and oil shale ash to reduce their storage giving practical and environmental protection use to the study results. The aims of the current study were to determine whether a short-term fertilization with oil shale ash and a mixture of wood ash and oil shale ash:

- increases the content of main nutrients (N, P, K, Ca and Mg) in the growth substrate and affects the pH of different peat layers;
- stimulates the production and affects the allocation of above- and belowground biomass of Silver birch (*Betula pendula* Roth) and Scots pine (*Pinus sylvestris* L.) seedlings.

2. Material and methods

2.1. Study site and treatments

The Puhatu experimental area is located on a cutaway peat-milling area in Ida-Viru County (Northeast Estonia) (59°19.368′N, 27°34.024′E). The study area was selected based on the economically viable distance (until 50 km) from the Estonian power plants. The area of the abandoned field at Puhatu is 1359.80 ha, and the peat harvesting was terminated around 1996 (Ramst et al., 2006). The average thickness of the well-decomposed peat is 0.9 m. The number of naturally renewed trees on the Puhatu cutaway peatland is very small. Therefore, some areas have no functioning drainage system and are seasonally flooded. According to the data from Jõhvi meteorological station the total amount of precipitation and the monthly average precipitation were respectively 759 mm and 63 mm in 2012; 683 mm and 57 mm in 2013; 588 mm and 49 mm in 2014 (Statistics Estonia, 2016). The average temperature according to the same station was 4.5 °C in 2012;