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Long-term effect of spruce bark ash fertilization on soil properties and tree biomass increment in a mixed scots pine-Norway spruce stand on drained organic soil

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Abstract. Ash contains all plant nutrients, except N, and is often used to facilitate forest growth and to prevent nutrient depletion potentially caused by harvesting. In this paper, we report effects of a large dose of spruce bark ash on soil properties and tree biomass increment in a mixed Scots pine-Norway spruce stand on drained organic soil in central Latvia, 12 years after ash application. Significant positive growth response after wood ash fertilization was recorded only for overstorey spruce. During the 12 years after fertilization the additional volume increment was 8.3 m^3 ha^{-1} or 0.7 m^3 ha^{-1} annually. The effect of wood ash application is long-term. Also 12 years after treatment fertilized overstorey spruces demonstrated 0.6 m^3 ha^{-1} additional annual volume increment compared to the controls. Additional diameter increment increased during the first 10 years after treatment but started to decrease in 2012. Results demonstrate that ash fertilization did not change N availability in the soil, and additional growth can be explained with improved supply of P, Ca, Mg and other nutrients. Ash application did not significantly influence the chemical composition of the O layer.

Key words: Ash Fertilization, Biomass Increment, Scots Pine, Norway Spruce, Soil Properties, Drained Organic Soil.

INTRODUCTION

Ash fertilization has a twofold effect. Firstly, it facilitates the return of nutrients to the forest ecosystem and, secondly, it helps to utilize wood ash generated as a by-product of combustion, whether for heat or power generation. Wood ash contains the following chemical elements: P, K, Ca, Mg, Mn, Cr, Cd, Pb, Na, S, As etc. (Kuokkanen et al., 2009; Lazdiņš et al., 2014). Several of those elements are essential to plant growth, especially phosphorus and potassium. The use of wood ash causes significant changes in soil physical and chemical properties. After fertilization pH value in the upper soil layer increases, as well as concentration of nutrients available to plants (K, Ca, Mg, B, P) (Saarsalmi & Mälkönen, 2001; Moilanen et al., 2002; Saarsalmi et al., 2004; Mandre, 2006). The presence of heavy metals (Cg, Pb, Cr) may limit the use of wood ash as fertilizer. Concern for environmental risks is most often related to concentrations of cadmium that often exceed the level allowed for fertilizers in agriculture (Evald, 1998; Korpilahti et al., 1998; Obernberger & Biedermann, 1998; Perkiomäki, 2004). Pitman (2006), however, suggests that additions of wood ash from known sources should not increase heavy metal loadings above those currently recommended.

The impact of ash fertilization on stand productivity is highly variable (Pitman, 2006; Reid & Watmough, 2014). It seems to be dependent on the already available nutrients in the soil, site fertility and soil type. Positive and fast growth response is recorded on nutrient-poor organic soils (Silfverberg & Huikari, 1985; Silfverberg & Hotanen, 1989; Ferm et al., 1992; Hytönen & Kaunisto, 1999; Ernfors et al., 2010). The effect, however, depends on the availability of nitrogen – in oligotrophic mires where there is a lack of available N ash fertilization effect can be minor (Moilanen et al., 2004). On mineral soils, the addition of wood ash is often targeted to counteract nutrient depletion caused by whole-tree harvesting.

One of the most significant advantages of wood ash is the long-term impact on the trees, compared to mineral fertilizers (Moilanen et al., 2002; Saarsalmi et al., 2012). It has been suggested that one single application of wood ash at 10 t ha^{-1} could replace nutrient losses from whole-tree and intense biomass harvesting sites, provided that additional N is added to create balanced input (Vance, 1996). However, also application of much higher doses (20–100 t ha^{-1}) of wood ash has been reported (Moilanen et al., 2012). It may be expected that in case of a larger dose the effects on other ecosystem parameters, e.g., ground vegetation development, soil properties and groundwater quality, will be more explicit.

The aim of the study was to determine the changes in tree growth, soil properties, groundwater chemistry and ground vegetation after fertilizing a mixed Scots pine-Norway spruce stand on drained organic soil with a large dose (50 t ha^{-1}) of wood ash. This particular paper presents results on long-term growth response and soil properties.

MATERIALS AND METHODS

Study site and plots

The study was conducted in a research forest in the eastern part of Latvia. This forest was already equipped with groundwater wells, since long-term hydrological measurements have been carried out there since 1963. A mixed pine-spruce stand on a former transition mire (drained in 1960) was chosen for the study (56°42´48´´N, 25°50´95´´E, 95 m a.s.l.). The site type according to the national classification system is *Myrtillosa turf. mel.* (Zalitis & Jansons, 2013). The soil type according to the WRB soil classification system is Hemic Rheic Histosols (Dystric, Drainic). A large dose of wood ash (50 tons ha^{-1}) was deposited at the study site in 2002 as part of the EU-funded project ‘Wood for Energy - a contribution to the development of sustainable forest management’ (*WoodEnMan*). It was decided to apply a large dose (50 tons ha^{-1}) of wood ash while during this project also impact on groundwater chemical composition was analyzed. One of the hypotheses was that a large dose of fertilizer would impair groundwater quality. The impact on groundwater chemistry was found to be insignificant but these results are not included in the current paper. Nine circular sample plots were established around already existing groundwater wells. Sample plots were treated with 50 tons of ash per ha, leaving a 1 m, 2 m and 3 m buffer zone (1 m – A1, B1, C1; 2 m – A2, B2, C2; 3 m – A3, B3, C3) around the groundwater wells (Fig. 1).

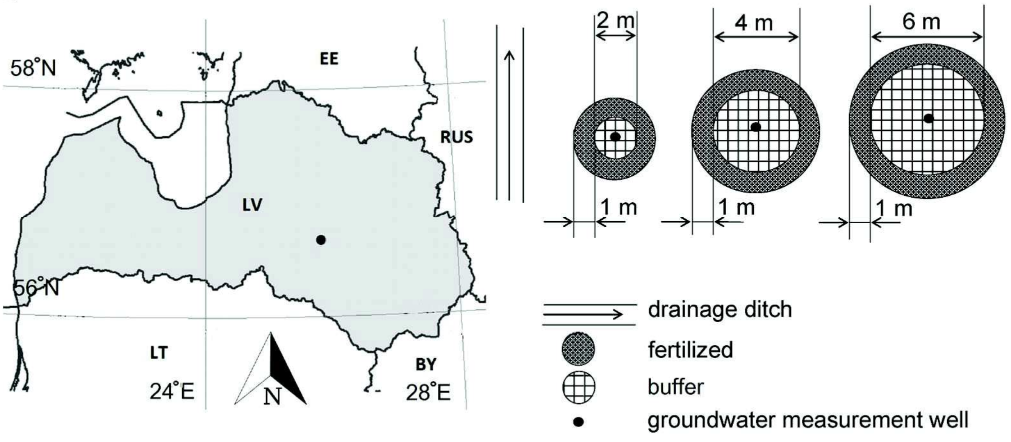

Figure 1. Study location and sample plot design.

Spruce bark bottom ash from sawmill *Vika Wood* was used for the project. The input of nutrients with ash was: $P\text{-}PO_4^{3-}$ 21.5 g m^{-2}, K 54 g m^{-2}, Ca 282 g m^{-2}, Mg 382 g m^{-2}.The content of heavy metals and sulfate in the ash was not available.

Before the ash applicaton in the spring 2002 soil (0–15 cm depth) pH was 5.5; soil NH_4-N content was 14.9 mg 100 g^{-1}, soil PO_4-P content was 0.6 mg 100 g^{-1}, soil K content was 5.1 mg 100 g^{-1}, soil Ca content was 94.6 mg 100 g^{-1} and soil Mg content was 51.1 mg 100 g^{-1}.

Stand measurements

Tree diameter at breast height (DBH) was measured in the plots treated with ash and in control plots. Control plots were established 25 m away from groundwater wells on a transect parallel to the wells. In total, 18 circular plots were measured – 9 treated plots and 9 control plots. The sample plot size for tree measurement was 500 m^2 (R = 12.62 m). In this plot, all trees with DBH > 14 cm were measured. In the plot with R = 6.64 m from the center, also all trees with DBH > 6 cm were measured, and in the northeast segment of the inner circle, – also all trees with DBH >2 cm were measured. Tree species, DBH, height and storey was determined for all measured trees.

Tree increment

As the stand is uneven-aged, fertilizer impact was analyzed separately for overstorey pine, overstorey spruce and second storey spruce. Increment cores were taken from 10 trees in each treated plot (at least 3 overstorey pines, 3 overstorey spruces and 3 second storey spruces if this number of trees was found) and from 15 trees in each control plot (5 trees from each group, respectively). In total, 19 overstorey spruce, 29 second storey spruce and 32 pine increment cores were collected from the fertilized plots and 33, 34 and 68 increment cores from the control plots, respectively.

The volume increment for each tree was calculated according to the equation (Liepa, 1996):

$$Z_v^{vp} = 10^{-4} \cdot \lambda \cdot d^2 \cdot \left(\frac{0.4 \cdot i \cdot u \cdot (+4)}{d} + Z_{\mathrm{L}} \right) \tag{1}$$

where: λ – stem volume coefficient (0.306 for pine, 0.326 for spruce); d – stem diameter, cm; L – tree height, m; i – radial increment, mm; u – bark thickness coefficient (1.103 for pine, 1.046 for spruce); Z_{L} – height increment, m.

Height increment was calculated according to equation (Liepa, 1996):

$$Z_L = \frac{2iL(ad + b)}{cd + 100} \tag{2}$$

where: a, b, c – height increment coefficients (-0.0642, 6.356, 27.105 for pine, -0.0256, 1.693, 5.794 for spruce).

Changes in theoretical annual increment are defined as additional increment and it can be positive, negative or without changes. Additional increment is the result of treatments influencing tree growth. Additional volume increment was calculated according to equation (3) (Liepa, 1996). The method is based on the assumption that potential average tree increment after treatment can be calculated from trees on control plot with similar growing conditions and age. Annual increment for individual trees before treatment in control plots must correlate with average annual increment before treatment in treated plots.

$$Z_M^{kp} = 12732.4\psi \left(GH^{\alpha} D^{\beta \cdot lgH + \varphi - 2} - G_t H_t^{\alpha} D_t^{\beta \cdot lgH + \varphi - 2} \right) \tag{3}$$

where: ψ, α, β, φ – tree growth coefficients ($1.654 \cdot 10^{-4}$, 0.5658, 0.2592, 1.5969 for pine, $2.311 \cdot 10^{-4}$, 0.7819, 0.3418, 1.1881 for spruce); G, G_t – basal area of tree stand and its prognostic value, m^2 ha^{-1}; H, H_t – average height of tree stand and its prognostic value, m; D, D_t – average diameter of tree stand and its prognostic value, cm; t – time interval of disturbance (years after fertilization), years.

Prognostic value of stand basal area:

$$G_t = \frac{D_t^2 \cdot G}{D^2} \tag{4}$$

Prognostic value of average stand diameter:

$$D_t = D - 0.1 Z_D^{kp} \tag{5}$$

where: Z_D^{kp} – average stand diameter cumulative additional increment, cm. Calculated according to equation (Liepa, 1996):

$$Z_D^{kp} = 2u\left(\sum_j^t i_j - \sum_j^t i_j'\right) \tag{6}$$

where: i_j – average stand radial increment in year j, mm; i_j' – prognostic values of average stand radial increment, mm. alculated according to power regression equation:

$$i_j' = \eta \cdot \left(i_{k;j}'\right)^{\rho} \tag{7}$$

where: η, ρ – coefficients of regression equation; $i_{k;j}'$ – average radial increment from control trees after year disturbance for k trees in j year, mm.

Annual increment of control trees from control sample plots must correlate ($r > 0.50$) with annual increment in treated plots, otherwise it is not used in calculations.

Prognostic value of average stand height:

$$H_t = H - Z_H^{kp} \tag{8}$$

where: Z_H^{kp} – average stand height cumulative additional increment, m:

$$Z_H^{kp} = \frac{HZ_D^{kp}(aD + b)}{u(cD + 100)} \tag{9}$$

Differences in the average value of stand characteristics between treated and control plots were analyzed with Student's t-test for two independent samples. Significance of additional increment after ash treatment was checked with Student's t-test for paired samples. It was assumed that there was no additional increment in the absence of ash treatment. Control trees were used to construct the trend of theoretical tree increment values for a 12-years period following treatment and this was compared with the measured values in the treated plots. Two alternative hypotheses were considered:

H_0: Additional increment after treatment is equal to zero;

H_a: Additional increment after treatment is higher/less than zero.

Sampling and analyses of soil and organic O layer

Soil and soil organic O layer were sampled in each sample plot in 3 repetitions. Soils were sampled at 0–10 cm, 10–20 cm, 20–40 cm and 40–80 cm depth using a soil sampling probe with a steel cylinder of 100 cm^3 volume. At the same place, O layer monoliths (10 x 10 cm) were sampled from each subplot using a stainless steel square soil sampler.

Soil and soil organic O layer samples were prepared and analyzed in the Forest Environment Laboratory of LSFRI Silava according to ISO methodology. Soil and soil organic O layer samples were prepared for analyses according to the LVS ISO 11464 (2005) standard. A fine earth fraction of soil ($D < 2$ mm) was used for chemical analysis. The following parameters were determined in the soil and soil organic O layer samples: bulk density according to LVS ISO 11272:1998; potassium (K), calcium (Ca) and magnesium (Mg) extracted with concentrated nitric acid and determined by flame atomic emission or absorption spectroscopy; phosphorus (P) extracted with concentrated nitric acid and determined according to LVS 398 (2002); total nitrogen (N) content determined using a modified Kjeldahl method according to LVS ISO 11261 (2002); organic and total carbon (C) content determined using elementary analysis according to LVS ISO 10694 (2006); and soil acidity (pH $CaCl_2$ and pH H_2O) potentiometrically measured in the supernatant suspension of a 1:5 soil:liquid (v/v) mixture according to LVS ISO 10390 (2002). The content of heavy metals and sulphate was not analyzed.

Statistical analysis

Kruskal-Wallis one-way analysis of variance was used for statistical testing of additional increment. One of the samples was the mean annual increment in treated plots. The other was mean annual prognostic increment, calculated from control trees with equation (7) as described above. Error bars and confidence intervals presented in figures and tables are confidence intervals at 95% confidence level. All data analysis was conducted with R software.

RESULTS

Stand characteristics

Stand characteristics are summarized in Table 1. Mean diameter (D) and mean height (H) characterizes dominant tree species, while basal area, standing volume and number of trees characterizes all trees in the plot. No significant differences were detected between the mean stand characteristics of treated and control plots (Table 1). The largest mean height, basal area, standing volume and number of trees were found in plot A, both in the treated and control subplots, while the lowest mean diameter, height and standing volume of dominant tree species were found in plot C. Trees in the B and C sample plots had suffered from windthrow and fungal diseases to a greater extent than in the A sample plots, which could have affected mean stand characteristics.

Table 1. Stand characteristics in treated and control plots

	Plot	Mean Diameter, cm	Mean Height, m	Basal Area, m^2 ha^{-1}	Standing Volume, m^3 ha^{-1}	Number of Trees, per ha^{-1}
Treated	A	25.4 ± 1.3	23.9 ± 0.4	31.3 ± 5.7	335 ±47	1067 ±470
	B	25.7 ± 1.3	21.7 ± 0.3	24.8 ± 5.1	248 ± 57	640 ±68
	C	24.3 ± 1.3	19.6 ± 0.8	21.1 ± 4.0	198 ± 26	587 ±151
	mean	25.1 ± 0.8	21.8 ± 1.2	25.7 ± 3.8	260 ± 45	764 ± 207
Control	A	25.4 ± 0.6	23.3 ± 0.6	28.5 ± 5.1	311 ± 45	867 ±449
	B	27.7 ± 1.7	21.9 ± 1.2	22.6 ± 1.1	226 ± 21	593 ±69
	C	24.4 ± 4.2	19.7 ± 1.8	24.0 ± 3.6	221 ± 36	813 ±193
	mean	25.8 ± 1.6	21.6 ± 1.3	25.1 ± 2.5	252 ± 34	758 ± 164

Soil and soil organic O layer properties

Soil acidity, total nitrogen, organic carbon, phosphorus and base cation (K, Ca, Mg) content and stock in soil and soil organic O layer were analyzed in the study site. Mean soil pH (H_2O) varied from 4.0 ± 0.2 (0–10 cm, plot B) to 5.3 ± 0.1 (40–80 cm, plot C) in control plots and from 4.9 ± 0.6 (10–40 cm, plot A) to 5.9 ± 0.2 (40–80 cm, plot C) in the treated plots. Sample plots with ash treatment showed significantly ($\alpha = 0.05$) higher soil mean, minimal and maximal pH values compared to control plots (Fig. 2). The largest differences (1.0 pH unit) were detected in the organic topsoil (0–10 cm): 5.2 ± 0.5 in the treated plots and 4.2 ± 0.2 in the control plots. Differences in the mean pH values between fertilized and control plots decreased with depth (0.6 and 0.4, at 10–20 and 20–80 cm depth, respectively). Also, the mean pH value of the soil organic O layer in the treated plots was significantly higher than in the control plots (5.0 ± 0.2 and 4.6 ± 0.1, respectively).

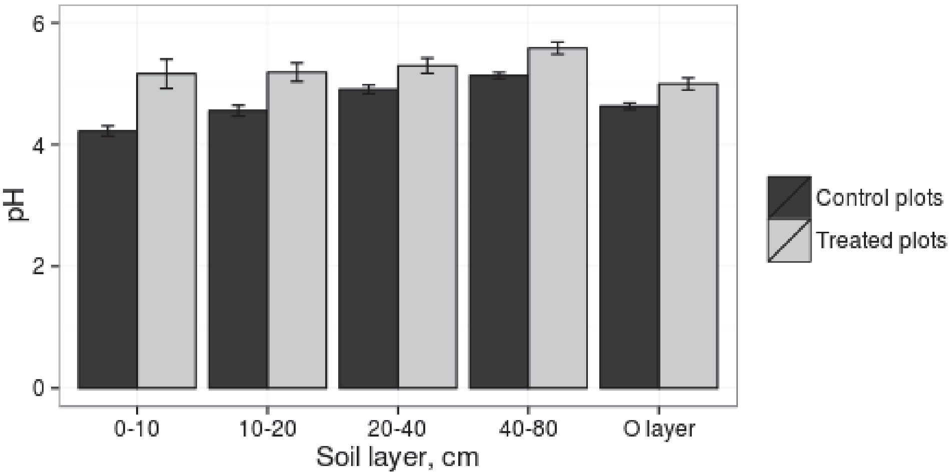

Figure 2. Mean pH (H_2O) in different soil layers.

The mean total N pool in the soil layers from 0–80 cm depth was 24.1 ± 1.7 t ha^{-1} in control plots and 23.5 ± 1.6 t ha^{-1} in treated plots. There was a trend toward a slight decrease in the total N pool in the upper soil layers (0-40 cm) of the fertilized plots but the differences were not statistically significant (Fig. 3). In addition, the N pool in the O layer was similar between treated and control plots (0.22 ± 0.2 and 0.21 ± 0.1 t ha^{-1}, respectively).

The mean total P pool in the soil layers from 0-80 cm depth was 0.63 ± 0.06 t ha^{-1} in control plots and 0.83 ± 0.13 t ha^{-1} in treated plots. The total P pool in the upper soil layer was significantly increased in the fertilized plots (Fig. 3). The mean P pool in the upper soil layer (0-10 cm) in the treated plots was 0.23 ± 0.09 t ha^{-1}, but in the control plots it was 0.11 ± 0.02 t ha^{-1} at the same depth. In the deeper layers, the P pool in the fertilized plots was still higher than in the control plots but the differences were not statistically significant. No significant differences were detected in the O layer.

The mean K pool in the soil layers from 0–80 cm depth was 0.22 ± 0.04 t ha^{-1} in control plots and 0.36 ± 0.05 t ha^{-1} in treated plots. The mean K pool in the sample plots with ash fertilization was higher than in the control plots at all analyzed depths, but statistically significant differences were only detected below 20 cm. According to results, K leaching into the deeper soil layers has taken place, while at the same time, better K supply in the upper soil layers is indicated.

Mean Ca pool in the soil layers from 0-80 cm depth was 17.2 ± 2.5 t ha^{-1} in control plots and 22.2 ± 3.7 t ha^{-1} in treated plots. Ca compounds in the fertilized plots were mainly found in the upper soil layer (0–10 cm), where the Ca pool was significantly higher than in control (Fig. 3). In the deeper soil layers in the fertilized plots, the Ca supply was slightly higher than in the control plots, but due to high variation, no statistically significant differences were detected. Below 40 cm depth, the Ca pools in the treated and control plots were similar. Consequently, most of the Ca supplied with the wood ash has accumulated in the upper soil layer. The Ca pool in the soil organic O layer was low and differences between treated plots and control were insignificant.

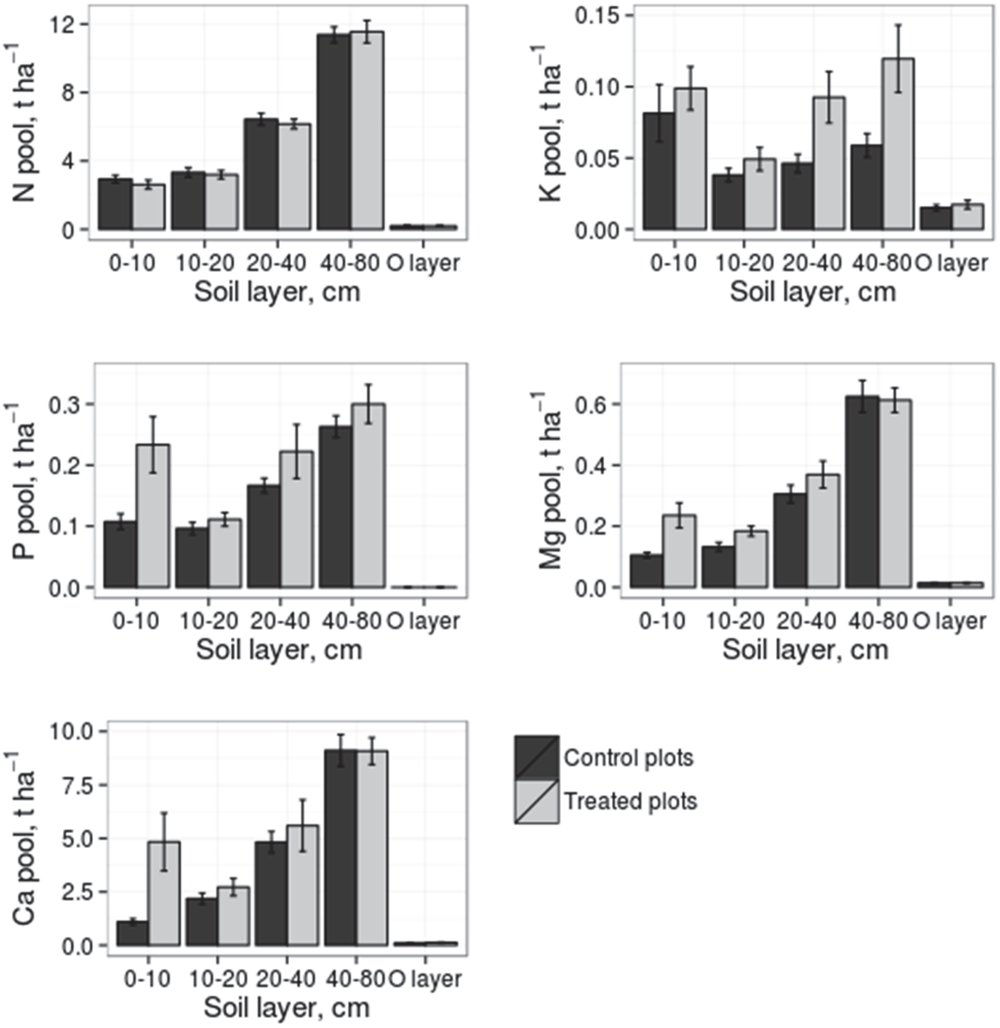

Figure 3. N, P, K, Ca and Mg pool in various soil depths and O layer.

The mean Mg pool in the soil layers from 0–80 cm depth was 1.17 ± 0.16 t ha^{-1} in the control plots and 1.40 ± 0.17 t ha^{-1} in the treated plots. The Mg pool in the soil was approximately 10 times lower than the Ca pool. A statistically significant difference between Mg pools in the treated and control plots was observed in the upper soil layer (0–10 cm). Down to 40 cm soil depth, the Mg pool in the fertilized plots was higher than in the control plots, but this difference was not statistically significant. Below 40 cm depth, no differences between Mg pools in the treated and control plots were detected (Fig. 3). In addition, similar to Ca, Mg has not leached deeper than the well-aerated upper soil layers, and is still available to the tree roots. No statistically significant differences between the soil organic O layer Mg pools in the fertilized and control plots were detected. The mean Mg pool in the soil organic O layer was 0.014 ± 0.002 t ha^{-1}.

The mean thickness of the soil organic O layer was 1.9 ± 0.2 cm in the control plots and 1.7 ± 0.1 cm in the treated plots. The mean bulk densities of the different soil layers in the control and treated plots are shown in Fig. 4. The mean bulk density of the soil organic O layer was 69.9 ± 6.5 kg m^{-3} in the control plots and 97.3 ± 10.0 kg m^{-3} in the treated plots. In half of the treated plots, soil organic O layer bulk density was higher than in the respective control plots. Differences in soil organic O layer thickness and bulk density can be explained by anthropogenic pressure, as different measurements are done regularly in the treated plots.

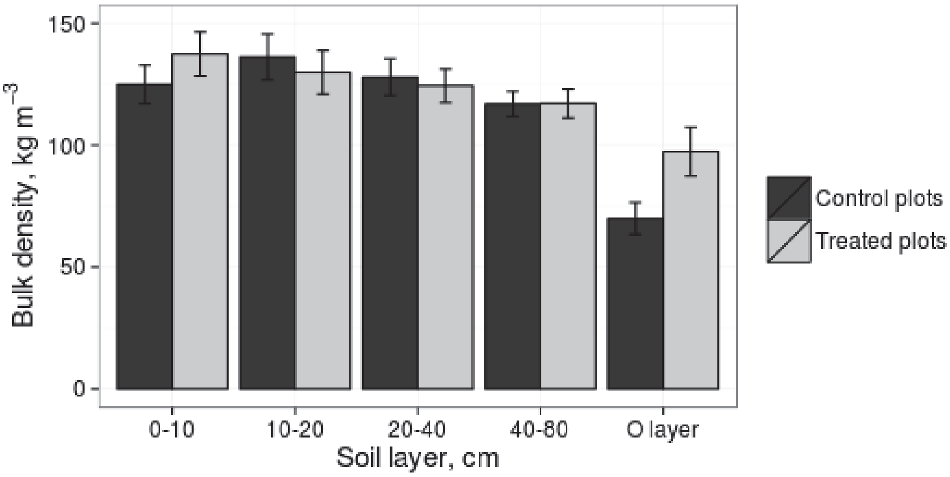

Figure 4. Bulk density of different soil layers.

Carbon stock in soil and biomass

The mean carbon stocks in different pools (living biomass and different layers of soil) in control and treated plots are shown in Table 2. In the study area, the largest carbon stock was located in the soil at 0-80 cm depth, with carbon stock ranging from 362 to 755 t ha^{-1} in this soil layer in different plots. A significant amount of carbon is stored in living tree biomass, ranging from 53.6 to 98.3 t ha^{-1}. The amount of carbon in the soil organic O layer does not exceed 12.6 tons ha^{-1}. No significant impact ($\alpha = 0.05$) of wood ash treatment on carbon stock in the different layers of soil and tree biomass carbon stocks was detected (Table 2). The measured differences were small and random.

Table 2. Carbon stock (t ha^{-1}) in living biomass and soils

Carbon	Control Plots			Treated Plots		
pool	A	B	C	A	B	C
Living biomass	84.7 ± 16.2	69.8 ± 4.3	76.3 ± 9.9	88.7 ± 13.4	75.1 ± 17.4	62.8 ± 9.0
Soil organic O layer	4.8 ± 0.3	6.3 ± 1.2	7.9 ± 0.8	7.1 ± 1.4	5.3 ± 1.2	9.4 ± 1.2
Soil, 0–10 cm	44.5 ± 4.5	86.0 ± 5.2	67.2 ± 4.5	51.1 ± 5.2	86.6 ± 7.4	64.1 ± 4.6
Soil, 10–20 cm	46.2 ± 2.6	104.2 ± 6.0	70.7 ± 4.6	43.4 ± 2.6	102.0 ± 1.7	62.9 ± 3.6
Soil, 20–40 cm	111.3 ± 7.2	191.2 ± 7.3	120.1 ± 10.6	105.8 ± 5.6	167.2 ± 8.4	130.0 ± 10.0
Soil, 40–80 cm	214.4 ± 8.0	312.4 ± 19.0	237.2 ± 20.4	220.5 ± 12.4	276.1 ± 14.5	288.1 ± 33.2
Soil, 0–80 cm	416.4 ± 9.8	693.8 ± 31.0	495.2 ± 58.2	420.7 ± 29.6	631.9 ± 23.5	545.1 ± 23.5

Tree increment

Increment cores were taken to analyze tree increment. With this method, it is possible to gather information about temporal changes in tree growth without time consuming, long-term observations. Analyzing growth only according to the tree ring width is not, however, the best approach, as the tree ring width naturally decreases with tree age. This parameter also does not allow the evaluation of economic gain. Volume increment is a better indicator for this purpose.

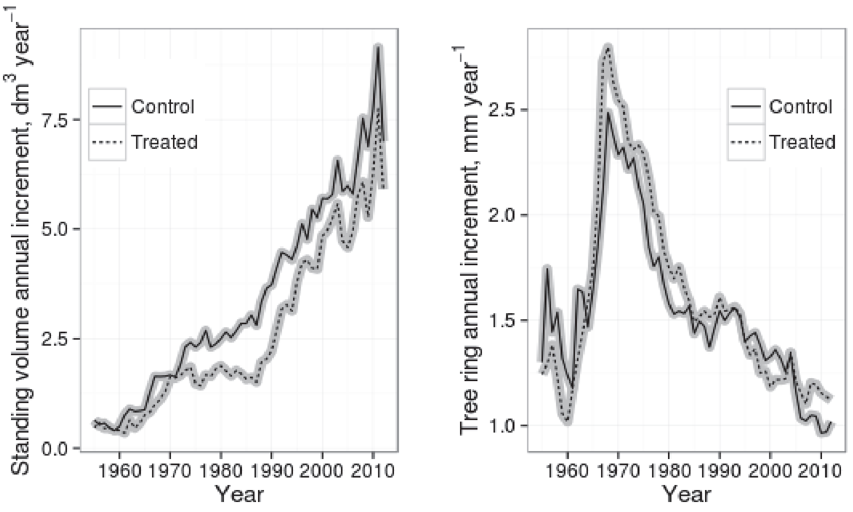

Figure 5. Mean standing volume and annual tree ring increment of pine and spruce combined in treated and control plots.

The most pronounced tree growth increase observed at the study site was noted in 1961, in the next year after drainage, indicating a very rapid response to the improved aeration and nutritional conditions. Since then, mean volume increment has displayed a steadily increasing trend, especially during the last 10 years. However, decreases in tree volume have also been observed in some growing seasons (Fig. 5). A strong correlation for annual tree ring and volume increment between ash-treated and control plots can be found before treatment ($r = 0.95$; $r = 0.91$), which is essential for calculations of additional increment.

Additional increment due to ash fertilization

Additional standing volume increment and additional diameter increment were evaluated to analyze the effect of ash fertilization on tree growth. Additional standing volume increment was calculated separately for pine overstorey, spruce overstorey and spruce second storey.

The effect of fertilization on the increment of pine and spruce was different (Table 3). After fertilization, the additional annual volume increments for spruce overstorey and spruce second storey were 0.68 m^3 ha^{-1} and 0.015 m^3 ha^{-1}, respectively. The additional volume increment for pine overstorey was negative, at -0.018 m^3 ha^{-1} per year. Only the additional volume increment for spruce overstorey was statistically significant ($p < 0.05$). The results suggest a positive response of spruce overstorey to fertilization, but no response in pine overstorey or spruce second storey.

Table 3. Additional standing volume increment and additional diameter increment

Parameter	Additional diameter Increment, mm		Additional standing volume Increment, m^3 ha^{-1}	
	12 years period	annual average	12 years period	annual average
Pinus sylvestris L. overstorey	-0.1	-0.01	-0.2	-0.02
Picea abies (L.) H. Karst overstorey	13.6	1.13	8.3	0.69
Picea abies (L.) H. Karst second storey	0.4	0.03	0.2	0.02
Mean of both species	13.8	1.15	8.2	0.68

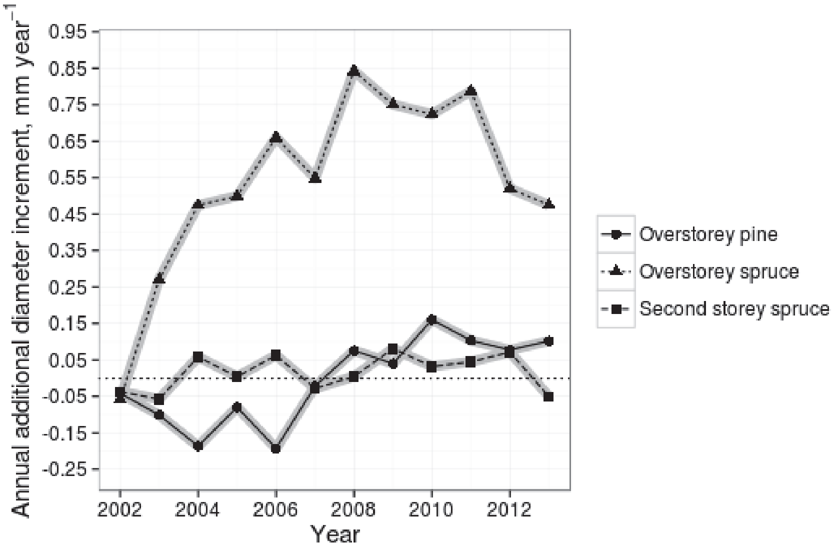

Figure 6. Mean annual additional diameter increment.

When temporal changes of the impact of wood ash application are analyzed, a small effect immediately after treatment (in 2002) can be seen (Fig. 6). Over time, the additional diameter increment of overstorey spruce increased, reaching its maximum in 2006–2011, or 5–10 years after ash application. Since 2012, the additional diameter increment has decreased. The additional diameter increment of pine tended to decrease during the first years following ash application, but then started to increase in 2007.

DISCUSSION

A large number of studies, especially those done in the Nordic countries, indicate that ashes can enhance the long-term productivity of some forested sites (Vance, 1996; Saarsalmi et al., 2001; Saarsalmi et al., 2004; Norström et al., 2012; Ingerslev et al., 2014). Dose rates of 10 t ha^{-1} have been suggested by Vance (1996) as being sufficient to replace all the nutrients lost by whole-tree harvesting. Our study assesses the long-term effect of spruce bark ash fertilization on organic soil properties and tree biomass increment in an area where 50 t ha^{-1} of ash were applied 12 years ago. According to literature, large doses of ash fertilizer may cause decline of woody shrubs and major changes to Bryophite and Lichen communities (Arvidsson et al., 2001; 2002; Jacobson & Gustaffson, 2001) and increase the likelihood of N leaching from sites with high N deposition (Högbom et al., 2001). Although no increase in cadmium or lead content of Vaccinuim species berries has been reported (Levula et al., 2000; Perkiömäki et al., 2003), in theory it may be possible, if a very high dose of fertilizer is applied.

Soil pH changes

Application of ash to the forest soil clearly has a liming effect (Jacobson et al., 2004; Ingerslev et al., 2014). Different long-term field trials indicate a sustained increase in pH in forest soil up to 30 years following ash application (Saarsalmi et al., 2012). In Denmark, studies by Ingerslev et al. (2014) indicate that the pH of the O-horizon increased significantly, by 0.9–1.7 pH units, at 2.5 years following wood ash application in a 44-year-old Norway spruce plantation with nutrient-poor soil. In Finland, 5–10 years after wood ash application (3 t ha^{-1} of loose wood ash) in coniferous stands (aged 31–75 yrs), the pH of the humus layer increased by approximately 1.0–1.7 pH units (Saarsalmi et al., 2004). Researchers in Finland resampled a Scots pine and Norway spruce site that had received an ash dose of 3 t ha^{-1} 16 years ago, and detected an increase in pH (0.6–1.0 pH units higher than control forest soils) for humic layers under canopies, with the effect most significant at the wetter sites (Saarsalmi et al., 2001). Our results confirm that the soil liming effect is maintained 12 years following spruce bark ash application, with the results indicating an increase of 1.0 pH units.

Nutrient pools in the soil

Results from investigations on the effects of wood ash application on soil are far from concordant, often due to differences in location, ash dose, site fertility and time span investigated (Norström et al., 2012). In general, however, addition of wood ash to organic forest soils has been shown to have a long-lasting effect. Due to increased pH, organic matter breakdown rates are accelerated and N is released for take-up by the trees (Pitman, 2006; Augusto et al., 2008; Ernfors et al., 2010). Similarly, our soil chemical analysis results show a slight decrease in the total N pool, in both the soil organic O layer and the upper soil layers (0–40 cm) in the plots given a spruce bark ash dose of 50 t ha^{-1} 12 years ago. In contrast to the N pool in the soil of the study plots, our results indicate statistically higher P, K, Ca and Mg pools in the treated plots, even 12 years after treatment, similar to previous studies (Eriksson, 1998; Saarsalmi et al., 2001; Arvidsson & Lundkvist, 2003; Jacobson, 2003; Jacobson et al., 2004; Saarsalmi et al., 2004). In the ash-treated plots, a significant amount of K has accumulated in the deeper soil layers. This reserve is not available to plants, as the groundwater level is, on average, 40–50 cm, and aerated soil and root depth is therefore limited to this depth. This leaching indicates that the trees have not been able to fully utilize the increase in K after ash fertilization. However, the K reserves remain there and may become available in favorable conditions, for example, in the event of groundwater level fluctuations. Naylor and Schmidt (1986) demonstrated that the availability of K was directly related to the amount added to the soil. The K dissolution rate and availability are dependent on soil pH (Naylor & Schmidt, 1986; Erich, 1991; Ohno, 1992).

Carbon stock

In long-term studies, wood ash has been shown to stimulate litter and cellulose decomposition and carbon mineralization (Moilanen et al., 2002; Perkiömäki & Fritze, 2002; Perkiömäki, 2004). It is noted that increasing the pH of soil may also result in carbon release due to increased microbial activity/growth and an increased decomposition rate of the humus layer (Kreutzer, 1995; Persson et al., 1995; Zimmermann & Frey, 2002; Corre et al., 2003). Furthermore, Rosenberg et al. (2010) found in Sweden that application of wood ash in high doses (6 Mg ha^{-1}) can deplete the organic C in soil and increase CO_2 evolution rates and heterotrophic respiration in the field, even 12 years after ash application at the N-rich Norway spruce site. Although our results show no differences in carbon stock between ash-treated plots and control plots, we could not assess the impact of ash fertilization on CO_2 emissions, as data about peat subsidence/growth rates are lacking for the study site. Even if we could measure peat subsidence/growth rates, peat stock is too high to detect any significant changes in carbon stock 12 years after fertilization. However, our results show a small but statistically insignificant increase ($p > 0.10$) on peat bulk density (0–10 cm), from 124.7 ± 12.9 in control plots to 137±14.1 ($\alpha = 0.10$) in ash-treated plots, indicating the possibility of increased peat decomposition rates.

Tree increment

According to the literature, the addition of loose ashes on drained peatlands usually increases forest growth (Moilanen et al., 2002; Moilanen et al., 2012; Saarsalmi et al., 2014). Insufficient supply of P and K is often regarded as one of the main factors limiting tree growth on drained peatlands in Finland, as no weathering of rock-forming minerals takes place in the peat (Magnusson & Hånell, 1996; Moilanen et al., 2005). The most pronounced positive response in tree stand to wood ash addition on peatlands is observed in nitrogen-rich sites, as wood ash contains all the major nutrients for plants, except N (Moilanen & Silfverberg, 2004; Saarsalmi et al., 2014). Ash application on mineral soils, however, is mainly aimed at counteracting soil acidification and returning the nutrients removed by harvesting, since on mineral soils tree growth is usually limited by the N that is evaporated during combustion. Therefore, a combination of ash and N fertilizer is often used to achieve the best results on mineral soils. However, even those results are variable. For example, Saarsalmi et al. (2004; 2006) reported that the combined addition of wood ash and N had no significant impact on the volume growth of 31- to 75-year-old conifer stands at 5 and 10 years after ash application. In addition, no significant treatment effect on the biomass growth of Scots pine was recorded in a study conducted in drained peatland sites in southern Sweden (Ernfors et al., 2010). However, in a study by Moilanen et al. (2002), Scots pine stem volume growth in a drained mire in the central part of Finland was substantially promoted for an extended period after treatment with 8 t ha^{-1} and 16 t ha^{-1} of wood ash.

Our results show that additional incremental growth as a result of ash fertilizer only occurred in overstorey spruce, with no significant impact on pine and second storey spruce increment. Tree age is a significant factor that may have influenced those trees' response to additional nutrient supply. Several trees are around 160 years old, and their reaction to changes to different factors is minor. Another likely explanation is the fact that study site is located in a confined aquifer discharge area. 86% of forests on wet and drained peat soils, and 60% of forests on wet and drained mineral soils in Latvia, are located in confined aquifer discharge areas, making it an essentially different situation from that in Fennoscandia (Indriksons & Zalitis, 2000; Zālītis, 2006; Zalitis & Indriksons, 2010). Discharge waters from the upper Devonian dolomite layers are rich in nutrients, and even in drained peatlands, where the peat layer is several meters deep and tree roots have no contact with the mineral soil, tree growth is very good, as nutrients are supplied by the sub-soil discharge waters. It is possible that in our study, the nutrient supply already is optimal for pine and additional fertilization does not have a significant impact. At the same time, spruce requires more nutrients than pine, and consequently shows a positive growth response to fertilizer. Second storey spruces suffer from unfavorable light conditions, and this could be the main factor limiting their growth. Considering the above, ash fertilization might be used to improve the growth of spruce stands on drained peat soils, while the effect may be minor in pine stands on drained peatland sites located in confined aquifer discharge areas.

The amount of ash applied, 50 t ha^{-1}, may be considered a very high dose. Even though even larger amount of peat ash (100 t ha^{-1}) has been applied in Finland (Moilanen, 2012), with no detrimental effects on the environment reported, wood ash is considered to have more pronounced effect than peat ash, both positive and negative. At our study site, no significant differences of N, P, K, Ca and Mg content in the groundwater in the year following fertilization were reported by Indriksons (2010). In 2012, ten years after ash application, the moss layer, significantly decreased in 2002, had fully recovered (Indriksons and Lazdina, unpublished data). However, the very high dose of the fertilizer potentially may have increased the content of heavy metals and sulfate in the soil and groundwater, and the lack of these data imposes limitations on the study. Heavy metal and sulfate content in the soil and groundwater should be analyzed next to be certain that the treatment has caused no negative long-term environmental consequences.

CONCLUSIONS

1. Significant positive growth response after wood ash fertilization was recorded for overstorey spruce only. For the 12 years following fertilization, the additional volume increment is 8.3 m^3 ha^{-1} or 0.7 m^3 ha^{-1} annually.

2. The effect of wood ash application is long-term. Twelve years after treatment, fertilized overstorey spruces demonstrate better growth than controls. Additional diameter increment increased during the first 10 years after treatment, but started to decrease in 2012.

3. In the fertilized plots, soil pH (H_2O) and the P pool were significantly higher than in the control plots (respective pH values: 5.2 ± 0.5 and 4.2 ± 0.2; respective P content: 0.23 ± 0.09 tons ha^{-1} and 0.11 ± 0.02 tons ha^{-1}).

4. The soil N pool is slightly higher in the control plots, but the differences are not significant. The results demonstrate that ash fertilization has not changed N availability in the soil, and a significant growth effect can be explained by the improved supply of P, Ca, Mg and other nutrients.

5. K has leached deeper into the soil and is mostly unavailable to plants at the present. However, with lowering of the groundwater level, it may become available.

6. Ca and Mg reserves are mostly concentrated in the upper soil layer (0–10 cm) and remain available to plants.

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