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Jyrki Hytönen¹ and Hannu Hökkä²

Comparison of granulated and loose ash in fertilisation of Scots pine on peatland

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Highlights

- Granulated ash and commercial PK fertilizer increased stand growth in similar way during 15-year study period.
- Loose ash gave stronger and faster response than granulated ash.

Abstract

The effects of wood ash fertilisation on tree nutrition and growth on forested peatlands has been studied using loose ash, but in practice, ash fertilisation is done almost exclusively with granulated ash. In this study, the effects of granulated ash and loose ash (both 5 Mg ha⁻¹) on the growth and nutrition of Scots pine (*Pinus sylvestris* L.) stands were compared between a nitrogen-poor and a nitrogen-rich site over 15 years. On the nitrogen-rich site, wood ash application was also compared with commercial PK fertilisation. On the nitrogen-rich site, mean stand volume growth increase over unfertilised control treatment during the 15 year study period using granulated ash and commercial PK fertiliser was of the same magnitude (on average, 2.2–2.3 m³ ha⁻¹ a⁻¹). However, when loose ash was used growth increase over control was higher (3.7 m³ ha⁻¹ a⁻¹). On the nitrogen-poor site, the mean growth increase gained by loose or granulated ash (1.4–1.5 m³ ha⁻¹ a⁻¹) over the unfertilised control treatment was not significant. Fertilisation with loose ash or PK increased foliar P, K and B concentrations already in the first or second growing season, following fertilisation on both sites. Granulated ash increased foliar P concentrations on the nitrogen-rich site less than loose ash. After an initial increase, foliar P, K and B concentrations decreased at the end of study period. On the nitrogen-poor site, foliar P concentrations were below the deficiency limit by the end of the study period.

Keywords *Pinus sylvestris*; fertilisation; granulation; nutrition; PK fertiliser; wood ash

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1 Introduction

In Finland, of the original 10 million ha of pristine peatlands, 4.7 million are drained for forestry (Korhonen et al. 2017). On poorly productive drained peatlands, the availability of nutrients, especially that of N, restricts tree growth. Their total area is estimated to be 0.6–0.8 million ha in Finland (Laiho et al. 2016). However, the largest changes in timber production as a result of peatland drainage have been observed in N-rich sites, which in their natural state have been treeless or sparsely forested fens (Hökkä and Ojansuu 2004). The naturally high N content of well-humified peat provides available N abundantly for trees, but such sites contain a lower quantity of other nutrients such as potassium (K) and boron (B) (Kaunisto and Paavilainen 1988; Kaunisto and Moilanen 1998; Laiho and Laine 1995), and deficiencies of K are common (Kaunisto and Tukeyva 1984; Silfverberg and Moilanen, 2008; Moilanen et al. 2010). Furthermore, the mineralisation of organic phosphorus (P) is often slower than the trees require, meaning that P deficiencies are common on peatlands (Moilanen et al. 2010).

The consumption of primary biomass for energy production generates increasing quantities of wood ash. In Finland and Sweden alone, the total amount of wood ash produced annually by the forest industry is estimated to be almost 1 million tonnes (Huotari et al. 2015). In recent decades, large amounts of wood ash have also been produced in other countries, especially in Europe and North America (Pitman 2006). Wood ash contains many of the essential nutrients (especially P, K and micronutrients) required for plant growth – except, notably, N, which is lost in the combustion process. Wood ash is alkaline and contains plant nutrients in the form of basic compounds. Thus, it acts both as a liming agent, reducing soil acidity, and as a fertiliser, supplying nutrients to plants (Saarela 1991). The recycling of wood ash, especially rich in P and K as fertiliser, has been studied quite intensively for several decades, and research results show that the use of wood ash has several advantages promoting tree growth and nutrition, and reversing the acidification of forest soil (Aronsson and Ekelund 2004; Pitman 2009; Huotari et al. 2015).

There are strict regulations for the content of the nutrients and the maximum concentrations of harmful compounds (e.g. heavy metals) for ash products (Huotari et al. 2015). The diverse effects of wood ash on the environment (trees, soil, vegetation, berries and mushrooms, fauna, watercourses) have been studied intensively during the past decades. However, no enrichment of heavy metals in food webs or leaching of heavy metals to watercourses has been reported in these studies (Huotari et al. 2015).

The use of wood ash as a fertiliser has increased over the last decade and is expected to continue to do so, e.g., due to growing interest in recyclable nutrient sources, new methods of pre-spreading treatments (granulation, self-hardening) and the development of spreading techniques. The importance of wood ash in Finland in the fertilisation of peatlands is also increasing, because there is no slow-soluble PK fertiliser on the market. Ash is currently estimated to be spread annually on more than 10 000 ha. Long-lasting effects of loose wood ash on the nutrient pools in surface peat, and on the nutrient status and growth of conifers growing on nitrogen rich peatlands have been reported in many studies (Silfverberg 1996; Silfverberg and Hotanen 1989; Moilanen et al. 2002, 2004, 2005, 2015; Hökkä et al. 2012). Loose ash fertilisation in N-rich drained peatlands is also a financially feasible management method (Moilanen et al. 2015; Ahtikoski and Hökkä 2019). However, no studies on profitability of fertilization with granulated ash based in experimental results are at the moment available. Also only few studies report long term effects of wood ash fertilization on N-poor sites and in some studies small growth increases have been reported also on such sites (Sikström et al. 2010; Moilanen et al. 2013).

Almost all studies on the effects of ash on the growth of trees, their nutrition, nutrient leaching, and the environment have been conducted with loose ash. However, nowadays almost all ash

used in forestry is stabilised and spread mostly in granulated form, or as pelletised or self-hardened forms. In stabilisation loose ash reacts with water and carbon dioxide (CO₂), forming compounds like hydroxides, carbonates, bicarbonates and minerals like gypsum and ettringite and resulting in hardening of the ash (Steenari et al. 1999). The hardening and granulation process can be controlled mechanically with rotation plates or strainers to form ash pellets and granulates. The main reasons for using stabilised ash have been that untreated loose or fly ash is difficult to handle, and its transportation and spreading in forests is technically difficult due to dust problems and problems in maintaining uniformity in the spreading and functioning of feeding devices (Hakkila and Kalaja 1983; Hakkila 1986). Loose ash also presents health risks to operators because of the fine airborne particles that may end up in the respiratory organs, and the impurities that may cause allergies when they come into contact with the skin (Juntunen 1982).

Stabilising of ash may reduce the leaching of nutrients. P and Ca and different heavy metals are highly insoluble in all types of ash fertilizers and granulation may still decrease their solubility (Nieminen et al. 2005). Thus, by using stabilised wood ash, the possible shock effects of a high pH on ground vegetation are considered to be avoided (Steenari et al. 1999). K is the most soluble nutrient in hardened wood ashes, but its loss rate from hardened ash is somewhat lower than from loose ash (Eriksson 1998; Nieminen et al. 2005) due to the formation of slower solubility compounds during the granulation process (Steenari et al. 1999). Nevertheless, Nieminen et al. (2005) found no differences in K release between self-hardened ash granulates and loose ash. According to Hytönen (1999), the release of K from the pellets is fast, but that of P quite slow. To our knowledge, the effects of granulated wood ash and loose wood ash on the growth and nutrition of Scots pine (*Pinus sylvestris* L.) have not been compared in field experiments.

We hypothesised that due to the slower solubility of some nutrients after stabilisation application of granulated ash would lead to lower initial growth response than loose ash. This would be seen also in the foliar nutrient concentrations. We also hypothesised that the effect of ash on growth of Scots pine stands growing on N-poor drained peatland would be small. Since the main fertilization treatment in peatland forests had for decades been commercial PK fertilization we compared effect of wood ash and PK fertilisation on the N-rich site.

2 Material and methods

The two study sites were located in Western Finland (Kannus: 63°53'N, 23°45'E and Sievi: 63°54'N, 24°27'E) within 40 km of each other. The studied peatland forests were drained to improve forest growth (the Kannus site in 1969, with ditch network maintenance in the early 1980s and in 1999–2000, the Sievi site in 1974). The Kannus site is classified according to Laine et al. (2012) as *Vaccinium vitis-idaea*-type peatland forest (PtkgII), and the Sievi site was originally less fertile low sedge bog, developing towards *Cladonia*-type peatland forest (Jätkg). In Finland, PtkgII is the most common drained peatland forest type, covering 37% of the total 4.7 million ha drained for peatland forestry. Jätkg-type peatland forests cover less than 2% of the total drained peatland area (Laine et al. 2012). Peat thickness was over 1 m on both sites.

The tree stands were pure Scots pine stands. At Kannus, the mean dominant height of trees at the beginning of the experiment was 9.3 m, and the volume was 41.1 m³ ha⁻¹. The stand density at the beginning of the experiment at Kannus was 860 trees ha⁻¹ (stems > 1.3 m in height). Due to the growth of shorter seedlings to a height of more than 1.3 m, the stand density during the 15-year study period increased to 1500–1600 trees ha⁻¹. At Sievi, the stand was a sapling stand, the dominant height of pines being 2.8 m. The number of trees above 1.3 m in height increased from 5100 to 6000 trees ha⁻¹ between 2003 and 2017.

Table 1. Treatments and amount of nutrients applied in the treatments.

| Treatment | Nutrients kg ha ⁻¹ | | | | | | |
|----------------|-------------------------------|----|-----|-----|-----|-----|----|
| | N | P | K | Ca | Mg | B | Zn |
| Control | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Granulated ash | 0 | 73 | 190 | 836 | 134 | 1.6 | 18 |
| Loose ash | 0 | 82 | 202 | 969 | 155 | 1.6 | 22 |
| PK fertiliser | 0 | 45 | 80 | 110 | 0 | 1.5 | 0 |

The experimental design was arranged in randomised blocks consisting of four treatments (1: control, 2: granulated ash, 3: loose ash, 4: PK fertilisation) (Table 1). At Sievi, PK fertilisation treatment was not applied, and thus only 3 treatments were studied. At Kannus, the experiment was replicated 9 times, and at Sievi twice. The ash was granulated at Uimaharju using the disc granulation method, and the loose ash came from the same granulation plant. The PK fertiliser for peatlands was applied at recommended rate of 500 kg ha⁻¹. Ash was applied at a rate of 5 Mg ha⁻¹ (dry ash), and the application amounts were calculated based on moisture content (granulated ash: 16.2%, loose ash 0.8%), and the spreading amounts were calculated accordingly. Ash was applied manually on the plots in the winter (15 January–22 February) in 2003, and PK fertiliser was applied in May (15–18 May). The size of the sample plots was 1600 m² at Kannus, and 500 m² at Sievi in control treatment, and 1500 m² in other treatments extending from one drainage ditch to another. The loose ash treatment received slightly more nutrients than the granulated ash treatment. The difference was 9 kg ha⁻¹ (11%) for P, and 12 kg ha⁻¹ (6%) for K (Table 1). The PK fertiliser was applied at the recommended rate and contained less nutrients than the ash treatments.

The average temperature sum (dd; +5 °C as threshold) at Kannus during the study years (2003–2017) was 1199 dd, the mean annual precipitation was 592 mm, and the mean annual temperature was 4.2 °C. At Sievi, the temperature sum was 1157 dd, the precipitation was 649 mm, and the mean annual temperature was 3.4 °C. The coldest growing season at both sites was 2008, when the temperature sum at Kannus and Sievi was 986 dd and 905 dd respectively. The warmest growing season was 2006, when the temperature sum at Kannus and Sievi was 1350 dd and 1329 dd respectively.

2.1 Measurements

The tree stand was measured on the plots at the beginning of the experiment and during growing season 5, 10 and 15 after the application of the fertilisers. At Kannus, 10 m wide sub-sample plots extending from one ditch to another and covering 25% of the area of the treatment plots for measuring the tree stand were established in the middle of the plots. At Sievi, one or two circular sub-sample plots were located in the centre of the plots (size 100–113.1 m²). The trees were mapped, and the diameter at breast height (DBH) and height of sample trees were measured. The volume of trees was calculated using Laasasenaho's (1982) taper functions. However, at Sievi, the trees were so small that DBH was measured only 10 years after fertilisation. At the beginning of the experiment and 5 years after fertilisation, only tree height was measured. Volume was calculated 10 and 15 years after fertilisation.

Current year needle samples for foliar analyses were taken from at least 5–7 trees per plot from the uppermost south-facing whorls of the trees 1, 2, 5, 10 and 15 years after the application of the fertilisers at Kannus and 1, 2, 7, 10 and 15 years after fertilisation at Sievi. The samples were dried at 60 °C and ground. The N was determined using the Kjeldahl method, except on the

last two sampling occasions, which were determined by CHN analyser. Total concentrations of K, Ca, Mg, iron (Fe), manganese (Mn) and copper (Cu) were determined using an atomic absorption spectrometer, except in the two last measurements, when nutrients were analysed after wet digestion in a microwave oven by ICP. Interpretation of the needle analyses was based on critical value results obtained in previous research, and deficiency limits and optimal concentrations of different nutrients in the needles of Scots pine on drained peatlands in Finland (Paarlahti et al. 1971; Reinikainen et al. 1998).

The bulk density of the 0–20 cm peat layer at Kannus was 170 g dm^{-3} , and at Sievi 50 g dm^{-3} (Maljanen et al. 2014). The corresponding total N contents were 2.7% and 0.6%.

2.2 Data analysis

The statistical significance of treatment effects was studied using IBM SPSS 22 statistics software. In testing the effect of fertilisation treatments on tree height, diameter, stand volume, and nutrient concentrations, time and treatment-by-time interaction effects were tested using the repeated ANOVA measures model. At Kannus, the height, diameter or stand volume measured at the beginning of the experiment at each plot was used as a covariate in analysing corresponding variables. At Sievi, the height at the beginning of the experiment was used as a covariate. When, in repeated ANOVA models, Mauchly's test indicated that the assumption of sphericity had been violated, the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity. A variance analysis was also conducted for each of the measurement occasions separately.

3 Results

3.1 Height and diameter

Fertilisation increased the dominant height and mean diameter of the trees at Kannus (Fig. 1A, B) according to repeated ANOVA measures model ($p < 0.001$). The height and diameter of trees in all fertilisation treatments differed significantly from the control, but there were no significant differences among the other treatments. In addition, there were significant fertilisation and year interaction ($p < 0.001$), indicating that the effect of fertilisation on dominant height and mean diameter increased over time. After 15 years, the dominant height of trees in control plots was 12.0 m, on plots fertilised with granulated ash 14.0 m, and on plots fertilised with PK 14.3 and on plots fertilised with loose ash 15.3 m.

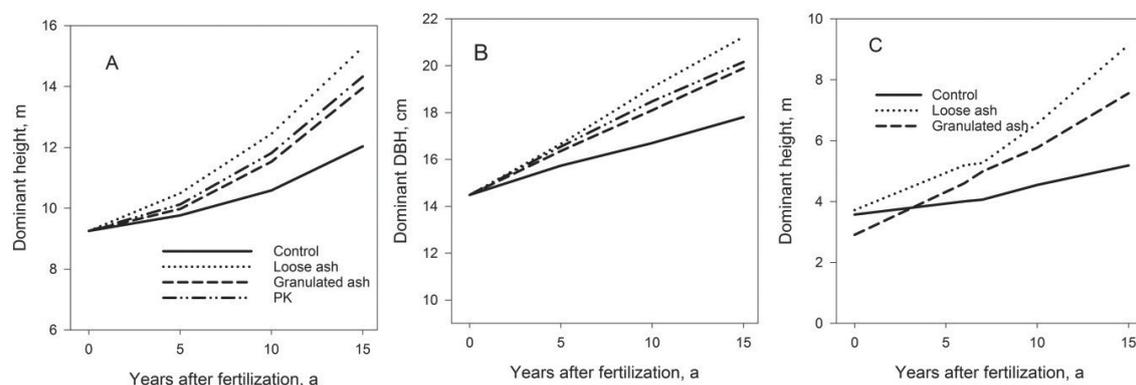


Fig. 1. Dominant height (A) and DBH (B) at Kannus experiment and dominant height at Sievi experiment (C).

At Sievi, the dominant height of trees at the beginning of the experiment was 2.7–2.9 m (Fig. 1C). At the end of the experiment, the dominant height of trees on control treatment was 5.2 m, while for those fertilised with loose and granulated ash, it was 9.1 m and 7.6 m, respectively. At Sievi, the main effect of fertilisation on the dominant height of trees was non-significant ($p=0.082$). However, there was significant ($p=0.027$) fertilisation and year interaction, showing that the effect of fertilisation increased over time.

3.2 Stand volume

Fertilisation enhanced stand volume development ($p<0.001$) at Kannus (Fig. 2A) according to repeated measures ANOVA. All fertilisation treatments differed significantly from the unfertilised control. Loose ash showed faster volume development than granulated ash and PK fertiliser treatments. However, the volume development of granulated ash and PK fertiliser treatments did not differ. There was also significant fertilisation and year interaction ($p<0.001$), indicating that the effect of fertilisation on stand volume development increased over time.

In terms of total volume, the difference between control treatment and fertilisation treatments increased from the first 5-year period (granulated ash: $3.1 \text{ m}^3 \text{ ha}^{-1}$, loose ash: $8.1 \text{ m}^3 \text{ ha}^{-1}$, PK: $5.4 \text{ m}^3 \text{ ha}^{-1}$) to the third 5-year period (granulated ash and PK: $17.2 \text{ m}^3 \text{ ha}^{-1}$, loose ash: $27.1 \text{ m}^3 \text{ ha}^{-1}$). At the end of the entire 15-year study period the differences in total volumes compared to control were $33 \text{ m}^3 \text{ ha}^{-1}$, $35 \text{ m}^3 \text{ ha}^{-1}$ and $55 \text{ m}^3 \text{ ha}^{-1}$ higher for granulated ash, for PK fertiliser, and loose ash, respectively. The total increase in volume for loose ash treatment was significantly higher than in other treatments, but granulated ash and PK did not differ from each other. During the entire 15-year study period, the mean annual growth increase with granulated ash and PK fertiliser was $2.2\text{--}2.3 \text{ m}^3 \text{ ha}^{-1} \text{ a}^{-1}$; whereas for loose ash it was $3.7 \text{ m}^3 \text{ ha}^{-1} \text{ a}^{-1}$.

At Sievi, 10 years after application, the volume in the control plots was $4.7 \text{ m}^3 \text{ ha}^{-1}$, and in the ash fertilised plots $14.6\text{--}14.7 \text{ m}^3 \text{ ha}^{-1}$ (Fig. 2B). Fifteen years after the application, the stand volume in the control plots was $7.1 \text{ m}^3 \text{ ha}^{-1}$, and in ash plots $28.0\text{--}30.3 \text{ m}^3 \text{ ha}^{-1}$. However, the effect of fertilisation on stand volume according to repeated measures ANOVA was not statistically significant ($p=0.064$). Time and fertilisation interaction was significant ($p=0.043$), indicating that the effect of fertilisation on volume increased with time. In terms of mean volume growth, significant increases of $6.8 \text{ m}^3 \text{ ha}^{-1}$ in the granulated ash treatment and $14.2 \text{ m}^3 \text{ ha}^{-1}$ in the loose ash treatment

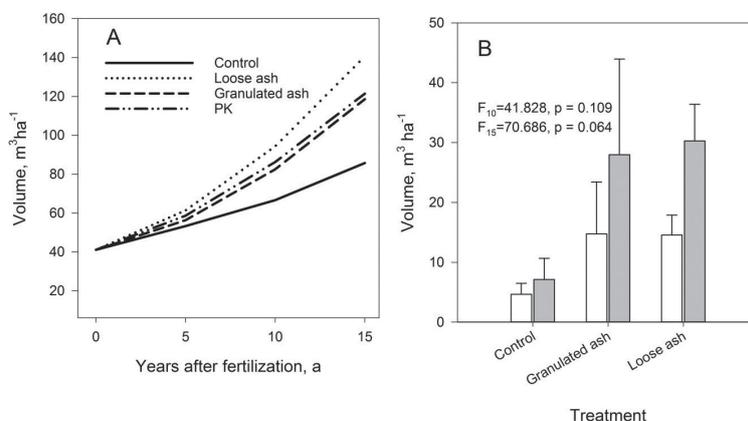


Fig. 2. Development of stand volume (A) in the Kannus and in the Sievi experiment (B) at time points 10 and 15 years after fertilisation. Bars show standard deviation.

compared to control during the third 5-year period (10–15 years) were observed. The difference in mean growth between granulated and loose ash was not statistically significant ($p=0.096$).

3.3 Foliar nutrient concentrations

The foliar N concentrations at Kannus in all treatments during the 15-year study period were above the deficiency limit, but at Sievi, N deficiency was observed on every sampling occasion in all treatments, with the exception of ash fertilised treatments two years after ash application (Figs. 3, 4). The foliar P concentrations were below deficiency limit one year after ash application at Kannus and two years after application at Sievi. In both experiments, loose ash fertilisation increased foliar P concentrations to above the deficiency limit by the 5th growing season. At Kannus, the granulated ash application resulted in lower foliar P concentrations compared to loose ash or PK. At Sievi, 10 years after wood ash application, foliar P concentrations were again at deficiency level. In the control treatment at Kannus, trees had K deficiency throughout the study period. At Sievi, no K deficiency was observed. Ash (at Kannus, also PK) application increased K concentrations, and although they later decreased, they remained mostly above the deficiency limit for the entire study period. Treatment had no significant effect on concentrations of Mg. No deficiency of B was detected at the study sites. At Kannus, PK fertiliser increased B concentration considerably one and two years after treatment, but the concentrations decreased after five years. Ash also increased B at both Kannus and Sievi.

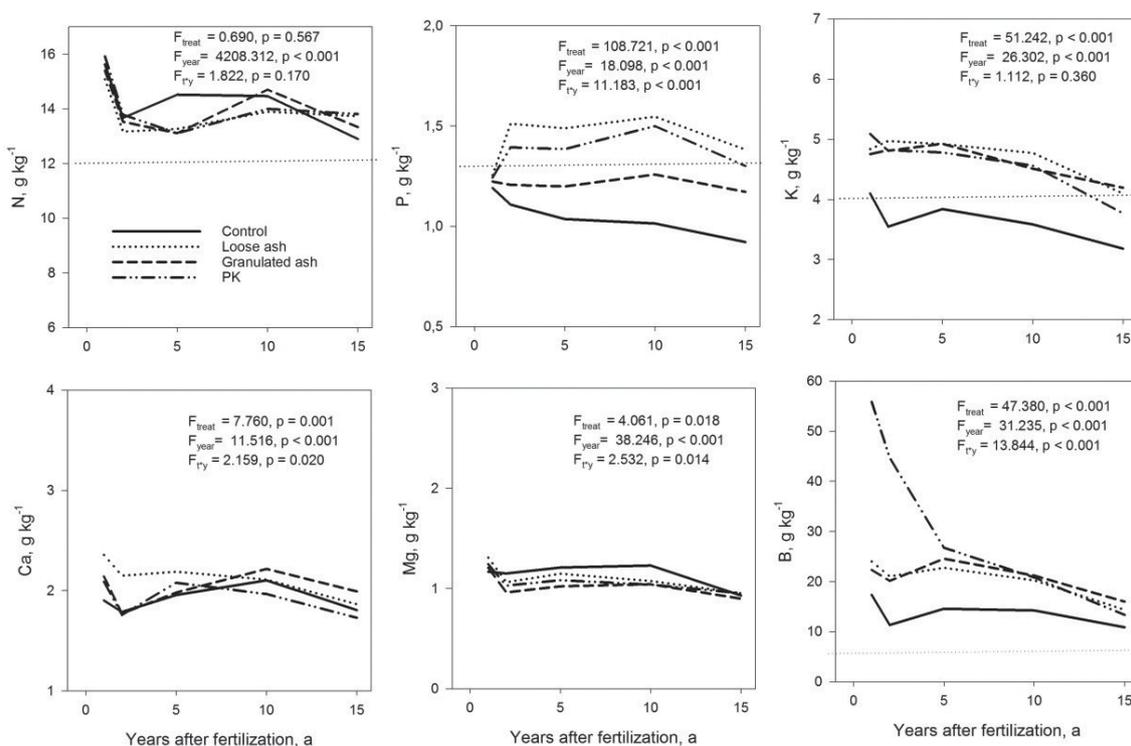


Fig. 3. Foliar nutrient concentrations at Kannus experiment. Dotted horizontal straight lines indicate deficiency limits for N, P, K and B (Paarlahti et al. 1971; Reinikainen et al. 1998). F and p values for treatment (F_{treat}), year (F_{year}) and treatment and year interaction (F_{t+y}) shown in the figures.

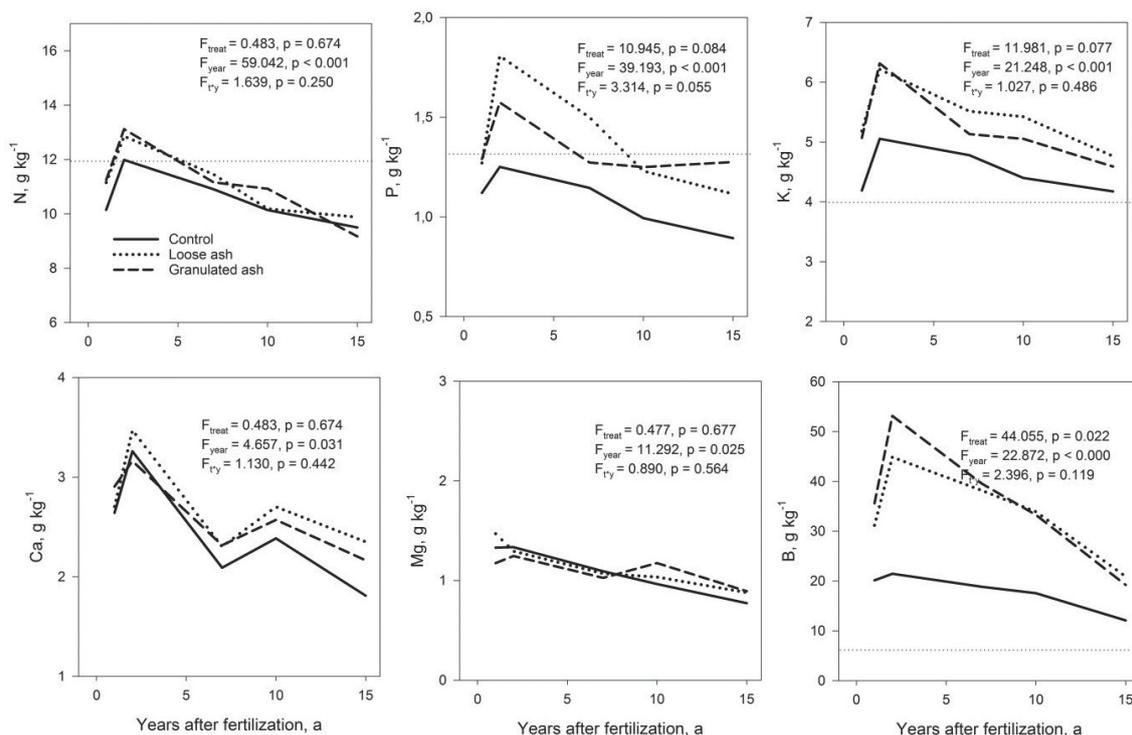


Fig. 4. Foliar nutrient concentrations in the Sievi experiment. Dotted horizontal straight lines indicate deficiency limits for N, P, K and B (Paarlahti et al. 1971; Reinikainen et al. 1998). F and p values for treatment (F_{treat}), year (F_{year}) and treatment and year interaction (F_{t*year}) shown in the figures.

4 Discussion

Wood ash fertilisation, whether loose or granulated, increased the growth of Scots pines at both sites. The Kannus site had quite high N concentration (2.7%) in the top peat layer, while the Sievi experiment was conducted on poor bog with N concentration of only 0.6% (Maljanen et al. 2014). The inherent differences in the nutrient content of the peat layer were also seen in the foliar nutrient concentrations of the unfertilised Scots pine needles. At Kannus, the trees had good N status, but severe P and K deficiency, which was aggravated by high N concentration leading to imbalanced N/K and N/P ratios. At Sievi, trees suffered from severe N deficiency (N concentration < 12 g kg⁻¹, Paarlahti et al. 1971; Reinikainen et al. 1988) and P deficiency (p < 1.3 g kg⁻¹), but had satisfactory K concentration.

The Kannus site was a typical target for ash fertilisation in terms of high N content in peat and deficiency of P and K in the tree stand. The average growth of 2.9 m² ha⁻¹ a⁻¹ on control plots during the 15-year study period was similar to that reported by Moilanen et al. (2015) for an unfertilised stand. Loose ash increased stem volume growth 2.2-fold, and granulated ash and PK fertiliser 1.7–1.8-fold compared to the control over the 15 years. The growth response was also comparable to those observed in several studies conducted at similar sites. Only loose ash has been used in previous studies. For example, Moilanen et al. (2012) reported a 3-fold growth increase following loose ash fertilisation after only 10 years at an N-rich drained peatland site. Moilanen et al. (2004, 2015) also found that in N-rich pine peatland, ash fertilisation more than doubled stand growth in 15–26 years. All the previous results (Moilanen et al. 2002, 2004, 2015) suggest that with a high peat N concentration like this study's Kannus site, the impact of ash fertilisation on tree growth will exceed the 15-year study period.

Because of its low N concentration in surface peat, Sievi site is not considered an optimal site for ash fertilisation. On the contrary, the inherent lack of N at the site suggests that ash application does not induce growth response in trees. However, even though the main effect of fertilization on height and volume was not significant the significant fertilization and time interaction indicated that effect of fertilization increased with time. Higher number of replications at the Sievi site would have been needed to detect significant differences. Results from the Sievi site can be compared to those reported by Sikström et al. (2010) from a fertilisation experiment on a drained poor pine bog in Southern Sweden. The tree stand was also very young and low-stocked at the outset, but in that study, unfertilised pine trees had a sufficient N status (Sikström et al. 2010). In the Swedish study, when ash containing 40 kg P and 145 kg K ha⁻¹ was applied, the growth increase varied from 1.6 to 1.9 m³ ha⁻¹ a⁻¹. This is close to the growth increase observed in this study for loose and granulated ash (1.3–1.5 m³ ha⁻¹ a⁻¹) at the Sievi site. The amounts of P (73–83 kg ha⁻¹) and K (190–202 kg ha⁻¹) in ash were higher in this study, but peat N was much lower. Also Moilanen et al. (2013) reported 13 years after ash fertilization (15 Mg ha⁻¹) the annual basal area increment on nutrient-poor site (low-sedge pine bog) being 1.7–1.8-fold compared with the control.

When similar doses of P were applied in experiments comparing ash and commercial PK fertilisation, Moilanen et al. (2004) showed that PK fertilisation initially increased stem volume growth more quickly than loose wood ash, but the effect of ash was stronger 15 years after application. However, in this study, ash contained 1.7–1.9-fold more P and 2.4–2.5-fold more K than PK fertilizer, and PK fertilisation increased growth less than fertilisation with loose ash, but at a similar level to granulated ash. In some other studies, wood ash application has also contained more nutrients than PK fertilisation. For example, in the study of Moilanen et al. (2015), wood ash (4.5 Mg ha⁻¹) contained 2.5-fold more P and 2.2-fold more K than PK, but ash increased Scots pine growth more than PK only 5 years after application. In the study of Silfverberg and Issakainen (2001) wood ash (>5 Mg ha⁻¹) contained 2–5 times more P and K than PK fertilizer, but height growth increase with wood ash was in 11–15 years only slightly higher than that obtained with PK fertiliser.

Loose ash gave a faster and stronger growth response than granulated ash, and the difference between loose ash and granulated ash continued throughout the 15-year study period at the nitrogen-rich site. However, at the nitrogen-poor site, the growth response to the ashes was similar. This may be due to the smaller trees at the nutrient-poor site requiring fewer soluble nutrients. Previously, pelletised ash has been shown in a greenhouse study to increase the growth of silver birch seedlings less than un-pelletised ash (Hytönen 1998). Nowadays, all wood ash is spread as granulated or self-hardened, and loose ash is used only in special cases, e.g., when spreading on treeless cutaway peatlands. Since loose ash gave stronger growth response than granulated ash, predicting growth response for granulated ash based on results from old wood ash fertilization experiments could lead to overestimation of growth. However, granulated ash proved to be as good a fertiliser as the commercial PK fertiliser at the nitrogen-rich site. Granulated ash treatment contained 9 kg ha⁻¹ less P and 12 kg ha⁻¹ less K than the loose ash treatment but these differences in nutrient amounts probably did not contribute to the differences in growth response. The P and K amounts exceeded those currently recommended (P 40–50 kg ha⁻¹, K 80–120 kg ha⁻¹) for nitrogen-rich, thick peated peatland forests (Vanhatalo et al. 2015). Based on previous studies showing that the positive effects of PK or ash application on stand growth on peatland sites have lasted for several decades, we expect the growth response to last much longer than this study's 15-year period (Moilanen et al. 2002; Moilanen et al. 2015; Hökkä et al. 2012).

The main reason for a slower growth response with granulated ash is probably the reduced leaching of nutrients after stabilisation, which at the nutrient-rich site was the probable reason for the lower foliar P concentrations. Based on foliar nutrient analyses, no other differences between

the ash types in nutrient uptake were found. Foliar K and B concentrations in needles were similar when loose ash and granulated ash were used, although formation of slower solubility compounds during the granulation process could somewhat lower K solubility (Eriksson 1998; Nieminen et al. 2005; Steenari et al. 1999). However, the release of K from the pellets is shown to be fast (Hytönen 1999), and Nieminen et al. (2005) found no differences in K release between self-hardened ash granulates and loose ash. In an incubation experiment, Callesen et al. (2017) found that granulated ash lost 35% of its Ca, Mg and K in seven years, but only 19% of its P. These results suggest that P is retained well in granulated ash. Thus, leaching of P after ash fertilisation would be minimal, as it is with loose ash (Silfverberg 1988; Steenari 1999; Nieminen et al. 2005). Due to the lower solubility of nutrients, use of granulated ash might also lead to a different pattern in the growth response: the maximum response may remain lower, but the fertilisation effect may last longer than with loose ash or commercial PK. This has impacts also on profitability of ash fertilization: one can expect that the financial performance of granulated ash in the short-term is lower than that found for ash fertilization in recent studies (Moilanen et al 2015). Still, the growth response in 15 years observed in this study compares to PK fertilization which has been judged as a financially profitable treatment by Moilanen et al. (2015).

Slow solubility of nutrients from granulated ash has also environmental benefits. With granulated ash, it is likely that increasing ash spreading areas does not entail increased risks of loads of P entering water courses (see Piirainen et al. 2012).

5 Conclusions

Granulated ash is a suitable fertiliser for peatland Scots pine, especially at N-rich sites. Compared to loose ash, the growth response in our study was slower but of similar magnitude to commercial PK. At the N-poor site tree growth was also enhanced by the application of granulated or loose ash. A decrease in foliar P and K concentrations suggests that a second application may be needed before the end of rotation. Due to the lower solubility of nutrients in granulated ash, its effect is expected to last longer than that of PK fertiliser or loose ash. However, more studies are needed to generalize the results.

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