




Article

Effect of High Concentrations of Wood Ash on Soil Properties and Development of Young Norway Spruce (*Picea abies* (L.) Karst) and Scots Pine (*Pinus sylvestris* L.)

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Abstract: Wood ash recycling can be a reasonable method for energy producers to decrease waste problems. Using wood ash as a fertilizer or liming material could improve soil macro and micronutrient content in peat soils. Therefore, the effect of wood ash on Norway spruce (*Picea abies* (L.) Karst) and Scots pine (*Pinus sylvestris* L.) juvenile growth and nutrient content in the soil after spreading wood ash in medium to high doses before and after planting seedlings was investigated in peat forests in the Eastern part of Latvia. The aim of the study was to evaluate the effect of high doses of wood ash on soil properties and the growth of planted Norway spruce and Scots pine seedlings up to 10 years after experiment establishment. Wood ash was applied a year before planting seedlings in doses of 5 and 10 t ha⁻¹ and right after planting in concentrations of 5, 10, 15, and 20 t ha⁻¹. Changes in macronutrient content (i.e., phosphorus [P], and potassium [K]) and tree height and diameter at breast height were measured at one and 10 years after establishing the experiment. Fertilization one year prior to planting the seedlings exhibited a positive response on tree height and diameter growth compared to fertilization after the seedlings were planted. Soil samples from fertilized plots one year after establishment contained more P and K in the soil than the control plots. Wood ash application of the highest doses did not reach the overdose limit, as the tree growth (height and diameter at breast height) results of fertilized plots were similar to those of the control fields; therefore, no significant negative effect on tree growth was discovered.

Keywords: fertilization; forest regeneration; liming; seedling growth; wood ash

1. Introduction

Wood ash application intensifies the increase of available nutrients in forest soils and improves forest production, however the effects of wood ash on tree growth differ between peat and mineral soils [1–5]. Wood ash fertilization has a long-lasting pH neutralizing effect on the soil organic layer and wood ash application counteracts soil acidity after forest harvesting of whole tree biomass (including logging residues and, in some cases, even roots) for energy production [4–6]. Therefore, wood ash could be used as an alternative mineral fertilizer and liming material because it primarily consists of metal oxides, hydroxides, carbonates, salts, and soil minerals [6,7]. Recycling ash may contribute to sustainable forest management, and it can be an environmentally acceptable solution to the waste problems of energy producers [8]. In Latvia, wood chip ash is deposited on waste disposal sites; thus, only a minor portion is used for fertilization and liming in farms. However, according to

the State Plant Protection Service registry data, interest in wood ash as a fertilizer has grown in the last few years, and currently, 24 companies have registered wood ash as a liming material.

Studies on the effect of wood ash application and soil chemistry of forest ecosystems have been carried out in Fennoscandia [8,9], and several small-scale experimental trials of wood ash usage for forest soil fertilization and liming were established in Latvia [10–13]. These studies have found that the utilization of ash by moving it back to forest mineral elements after the burning of organic matter for energy production could be defined as the “recycling of nutrients”, “fertilizing”, and “liming”. These methods are effective for stabilizing soil pH, enriching the soil with phosphorus (P), potassium (K), and micronutrient elements (zinc, boron, copper, etc.), especially in peat soils (due to the fact that wood ash does not contain nitrogen, however peat soils are nitrogen rich in comparison to mineral soils where nitrogen is the growth limiting element), and decreasing the need to deposit wood ash in waste disposal sites or landfills [14–24].

In general, no short-term growth effect of wood ash application has been found on mineral soils; however, recycling wood ash and using it as a fertilizer with other macronutrients or fertilizers may affect stand growth in different ways over a longer period [5]. On nitrogen (N) rich organic soils, a substantial growth increase is usually seen [25,26]. However, wood ash application can deplete organic carbon (C) in locations with N-rich soil [27]; therefore, experiments and investigations are needed to determine the potential and ecological consequences of wood ash recycling. The application of wood ash leads to changes in mycorrhizal fungi communities, increased species richness, and higher Shannon diversity index in fertilized plots compared to control plots [28].

The share of wood as a renewable fuel for energy and the increase in pellet production are factors that re-actualize investigations about the effect of wood ash as a source of nutrient elements for forest trees in the long term, therefore such investigations were done on experimental fields established several years ago. If forests within the Nordic and Baltic regions functioned as a “deposit” for the wood ash coming from the total harvest of wood for energy within the region, then the forests would receive an average of 0.2 to 0.5 t ha⁻¹ of dry wood ash within one rotation period [8]. Recommended wood ash doses in the rotation period are 1–2 t ha⁻¹ and 0.7–1.5 t ha⁻¹ for Norway spruce (*Picea abies* (L.) Karst) and Scots pine (*Pinus sylvestris* L.), respectively [29]. In the trial, high doses of wood ash are used to determine both positive and negative effects on plant development at an early stage and to assess the effects on the nutrient elements in the soil. Therefore, the aim of this study is to characterize the influence of high doses of wood ash on soil properties and the growth of Norway spruce and Scots pine seedlings up to 10 years after planting.

2. Materials and Methods

2.1. Study Site

The research site is located in the Kalsnava district in the central part of Eastern Latvia (56°42′ N. latitude, 25°50′ E. longitude), approximately 150 km from the Baltic Sea. The research area is located on the border between continental and marine climate conditions. The average air temperature is +5 °C to +6 °C (January –5 °C to 6 °C, July +16 °C to +18 °C). The average precipitation in previous years before planting was 797 mm [10]. The experiment was established on restoration site on homogenous drained fertile (grass) peat soil in the forest type *Myrtillosa mel.* [30]. Experimental plots were divided into 4 random blocks and total study site area was 0.2 ha, thus a single experimental plot size on average was 2.7 m². The study site design is presented in Klavina et al. [31]. Soil was prepared manually in each plot, the understory plants were removed, and the top soil layer was overturned.

The study site consists of 46 experimental plots (with 50 cm buffer zones between the plots) established with two tree species: Norway spruce and Scots pine. Altogether 18 spruce plots and 28 pine sample plots were established with two years old spruce containerized seedlings and one year old pine containerized seedlings obtained from JSC “Latvia’s State Forests” tree nursery. The seedlings met basic operational standards in terms of seedling morphological parameters. In each experimental

plot, approximately 70 containerized seedlings were planted in rows with 0.5×0.5 m spacing (Figure 1). The experimental plots of the Norway spruce consisted of randomly assigned plots with six replications for control and twelve replications with fertilization. Wood ash in doses of 0 (control group) and 5 and 10 t ha^{-1} (medium dose before) was applied in May 2003—one year before the spruce stand establishment. For Scots pine, the experimental plots consisted of randomly assigned plots with 6 to 8 replications for each type, where wood ash was applied a year prior to planting (in May 2003) in doses of 0 (control group) and 5 and 10 t ha^{-1} (medium dose before). In May 2004, in each plot seedlings were planted and the wood ash with doses of 0 (control group), 5 and 10 t ha^{-1} (medium dose after), or 15 and 20 t ha^{-1} (high dose after) was applied afterwards. Wood ash was applied manually on all the study plots (same method prior and after planting) with a surface spread approach.

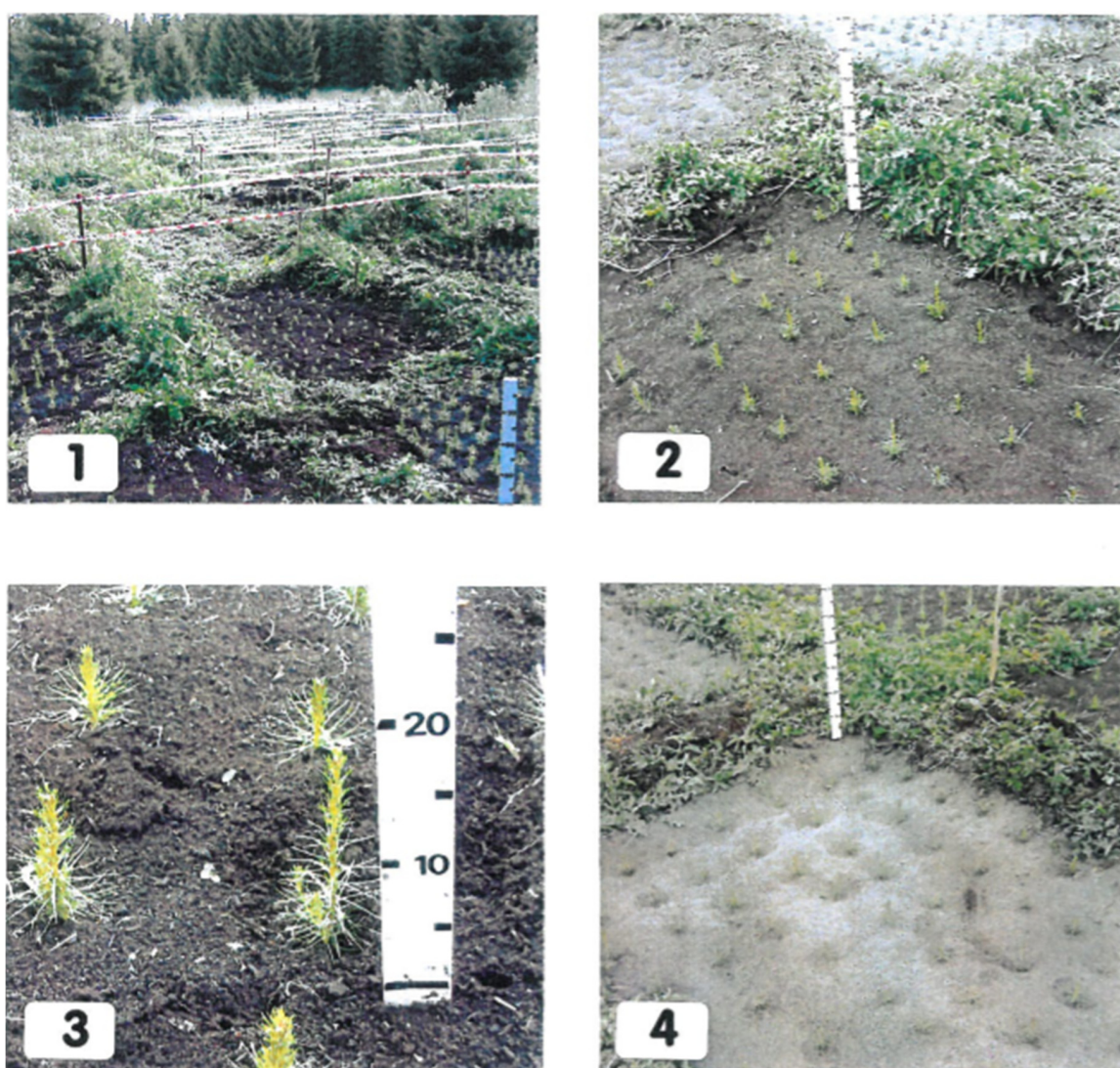


Figure 1. Experimental plots of wood ash fertilization (1 = experimental plots in the year 2004, 2; 3 = plots fertilized one year before planting seedlings, 4 = experimental plot fertilized right after planting seedlings) [10].

The medium dose (5 to 10 t ha^{-1}) of wood ash was calculated and assumed to last for a 5-year period, with the high dose (15 to 20 t ha^{-1}) of wood ash calculated to last for a 10-year period. The ash used for the experiment was alkaline ($\text{pH} = 12.44$); its nutrient content was average compared to that found by other scientists (Table 2). The experiment soil analysis established that the trial was conducted on an N-rich site; therefore, no additional N fertilizer was added.

One year after the experiment establishment, approximately half of the seedlings were removed from the sample plots for the investigation of root and stem biomass. Moreover, 10 years after the establishment of the experiment, the tree height and diameter at breast height (DBH) of the surviving and standing dead trees were measured. Originally, standing dead trees were measured to assess information of tree dimensions (H and DBH) at which self-thinning due to species competition occurred and at what wood ash doses. A sampling of the soil for nutrient analysis was conducted in each plot. Soil samples were taken from every experimental plot at four depths (0–10 cm, 10–20 cm, 20–40 cm, 40–80 cm).

Soil samples were prepared for analyses according to the LVS ISO 11,464 (2005) standard, and the parameters evaluated in the soil samples were the total N content using the modified Kjeldahl method according to LVS ISO 11,261 (2002). The available phosphorus ($P-PO_4^{-3}$) content was determined according to LVS 398 (2002), and the exchangeable K was extracted with ammonium acetate and determined using flame atomic emission spectroscopy.

2.2. Data Analysis

The generalized linear model was used to determine the significance of differences among the plots with various wood ash treatments. Mixed effect models were used for analysis where the plot ID was taken as a random factor, and the year of fertilization and dose combination were used as influencing factors.

3. Results

3.1. Fertilization Effect on Soil Chemical Composition one Year Afterwards

Wood ash is a source of K, and after fertilization, additional amounts of macronutrient elements are available for tree development. The K content in the soil of the pine sample plots one year after the application of wood ash increased two to six times in comparison to the control plots, depending on wood ash concentration (Figure 2). The content of K in the control plots was an average of $6.1 \pm 2.0 \text{ mg kg}^{-1}$, but after treatment with wood ash, the K content in the soil increased two to six times in the first year (differences are statistically significant). In the sample plots where wood ash was applied in medium doses ($5 \text{ to } 10 \text{ t ha}^{-1}$) before planting the seedlings, the K content was $11.9 \pm 2.1 \text{ mg kg}^{-1}$. However, treatment with medium doses ($5 \text{ to } 10 \text{ t ha}^{-1}$) right after planting resulted in K increases of up to four times ($25.5 \pm 9.5 \text{ mg kg}^{-1}$), but high doses ($15 \text{ to } 20 \text{ t ha}^{-1}$) of wood ash resulted in a K content of $37.8 \pm 9.8 \text{ mg/kg}$, which increased up to six times in comparison to the control field. In the spruce sample plots, the K amount in the control field was $6.0 \pm 1.7 \text{ mg kg}^{-1}$. In plots where wood ash was applied before planting, K increased to $7.9 \pm 2.0 \text{ mg kg}^{-1}$; however, no significant differences were observed.

Phosphorus (P) is one of the problematic or even lacking macronutrient elements in acid peat soils. The content of P in the soil after the application of wood ash was higher in comparison to the pine control plots. The average amount of P in the control plots was $0.22 \pm 0.06 \text{ g kg}^{-1}$, but after a year of the ash treatment, the P content in the soil increased by approximately two to three times in all sample plots (Figure 3). The lowest amount of P ($0.43 \pm 0.26 \text{ g kg}^{-1}$) between plots (excluding the control) occurred with the medium dose ($5 \text{ to } 10 \text{ t ha}^{-1}$) of ash applied a year before planting. The application of medium doses of ash after planting resulted in a significant increase in P content to $0.53 \pm 0.17 \text{ g kg}^{-1}$, but treatment with high doses ($15 \text{ to } 20 \text{ t ha}^{-1}$) of ash exhibited the highest content of P in the soil at $0.57 \pm 0.14 \text{ g kg}^{-1}$. In spruce sample plots, the P content in the soil increased in fertilized plots in comparison to the control plots. The lowest P amount in the soil was observed in the control plots ($0.31 \pm 0.05 \text{ g kg}^{-1}$); however, in the fertilized plots, the P content increased to $0.53 \pm 0.18 \text{ g kg}^{-1}$. The differences were noticeable but not statistically significant ($p > 0.05$) between the control and fertilized spruce plots.

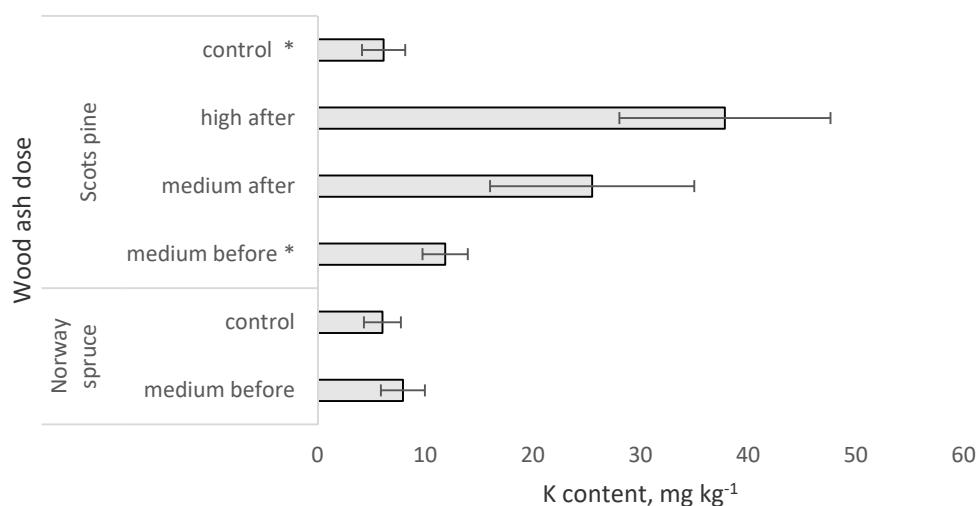


Figure 2. Content of potassium (K) in the soil a year after planting the seedlings fertilized using different wood ash doses (5 to 10 t ha⁻¹ = medium dose before planting seedlings, 5 to 10 t ha⁻¹ = medium dose after planting seedlings, 15 to 20 t ha⁻¹ = high dose after planting seedlings, and control = untreated plots, 0 t ha⁻¹; SP: Scots pine, NS: Norway spruce; the confidence interval is represented by vertical error bars, * indicates significant differences between treatments).

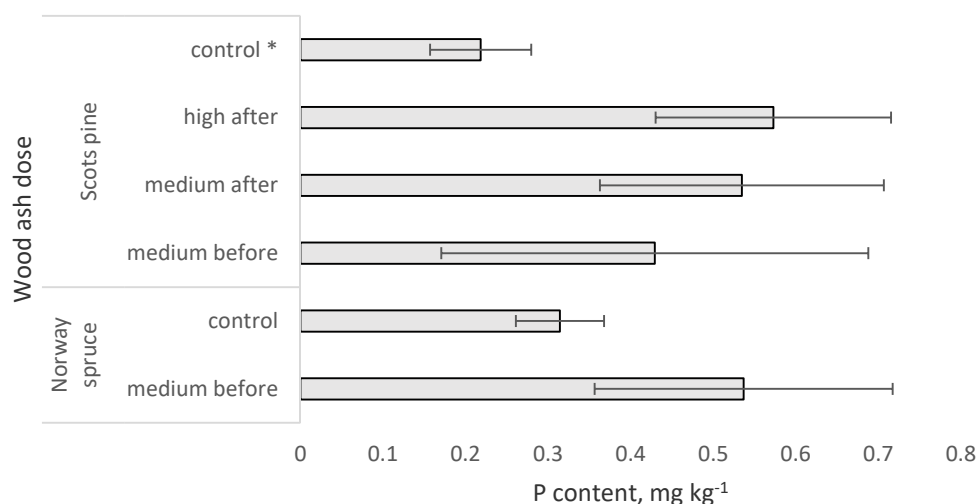


Figure 3. Content of phosphorus (P) in the soil a year after planting seedlings fertilized using different wood ash doses (5 to 10 t ha⁻¹ = medium dose before planting seedlings, 5 to 10 t ha⁻¹ = medium dose after planting seedlings, 15 to 20 t ha⁻¹ = high dose after planting seedlings, and control = untreated, 0 t ha⁻¹ plots; SP: Scots pine, NS: Norway spruce; the confidence interval is represented by vertical error bars, * indicates significant differences between treatments).

After wood combustion, most nutrients (except N) are retained in the ash, and the ash can be used for soil amendment, altering the soil properties. The ammonium (NH₄) content in the soil of pine plots varies from 9.3 ± 1.4 g kg⁻¹ (high dose after planting) to 12.3 ± 3.0 g kg⁻¹ (medium dose prior to planting); however, the changes are not significant after wood ash application with any dose; thus, the highest nitrogen content after one year was observed in plots where ash was applied a year before planting the pine seedlings (Figure 4). Similar tendencies were observed in spruce plots, where the highest N content was observed in sample plots where wood ash was applied (10.8 ± 0.9 g kg⁻¹), and the lowest amount was in control plots (9.6 ± 2.1 g kg⁻¹). However, no significant differences were observed.

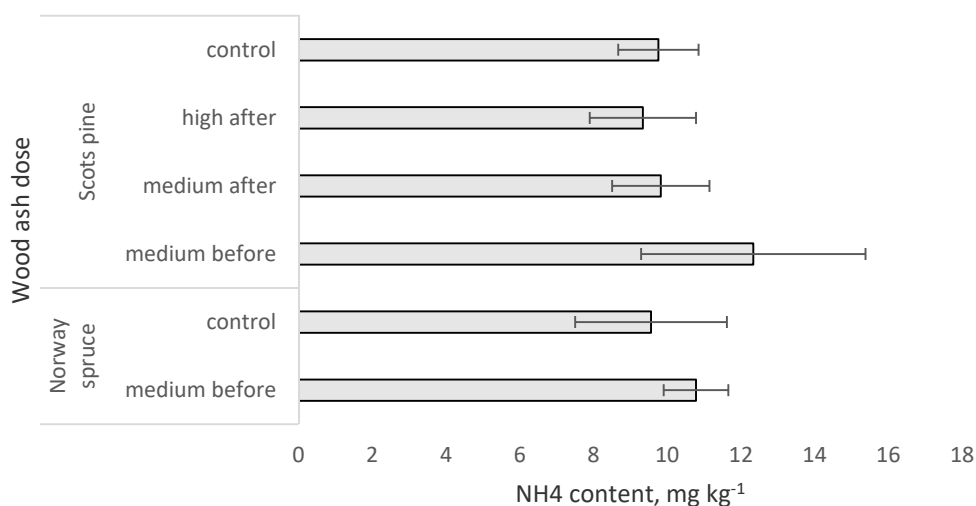


Figure 4. Content of NH_4 in the soil a year after planting seedlings fertilized using different wood ash doses (5 to 10 t ha^{-1} = medium dose before planting seedlings, 5 to 10 t ha^{-1} = medium dose after planting seedlings, 15 to 20 t ha^{-1} = high dose after planting seedlings, and control = untreated plots, 0 t ha^{-1} ; SP: Scots pine, NS: Norway spruce; the confidence interval is represented by vertical error bars).

3.2. Ten Years after Fertilization

After 10 years, no significant difference ($p > 0.05$) was observed between sample plots; however, in a 10-year period, the P content available for plants in soil in pine control fields was $1.8 \pm 0.31 \text{ g kg}^{-1}$ (Figure 5). In pine dominated plots where wood ash was applied a year before planting, the content also reached $1.8 \pm 0.37 \text{ g/kg}$. The application of a medium dose of ash after planting resulted in a P content increase to $1.6 \pm 0.24 \text{ g kg}^{-1}$, but treatment with high doses (15 to 20 t ha^{-1}) increased the P content in the soil to $1.7 \pm 0.27 \text{ g kg}^{-1}$. In spruce plots, the P content in control plots was $1.86 \pm 0.27 \text{ g kg}^{-1}$, while in fertilized plots the P content reached $2.2 \pm 0.34 \text{ g kg}^{-1}$.

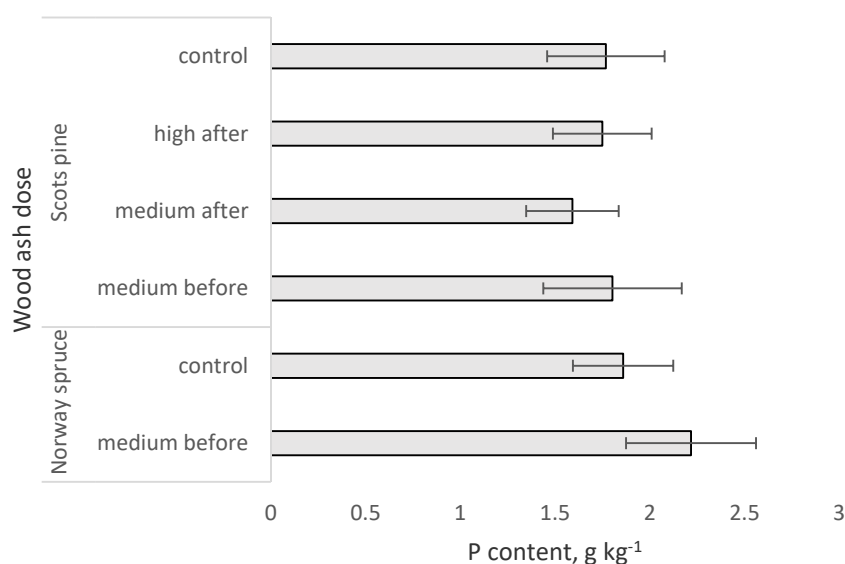


Figure 5. Content of phosphorus (P) in the soil 10 years after planting seedlings fertilized using different wood ash doses (5 to 10 t ha^{-1} = medium dose before planting seedlings, 5 to 10 t ha^{-1} = medium dose after planting seedlings, 15 to 20 t ha^{-1} = high dose after planting seedlings, and control = untreated plots, 0 t ha^{-1} ; SP: Scots pine, NS: Norway spruce; the confidence interval is represented by vertical error bars).

Ten years after the application of wood ash, differences in K content between treated and untreated plots are not as marked because the control plots have the highest K content ($372.5 \pm 102.1 \text{ mg kg}^{-1}$) in comparison to other pine-dominated plots (Figure 6). However, in spruce plots, the situation is inverted because the K content in control plots had a value of $270.9 \pm 71.3 \text{ mg kg}^{-1}$, but in fertilized plots, the K content was $299.6 \pm 65.3 \text{ mg kg}^{-1}$. In addition, the N content in the soil 10 years after wood ash application did not differ statistically significantly between tree species or wood ash doses. The N content in the soil varied from $25.4 \pm 1.8 \text{ g kg}^{-1}$ (medium dose before planting) to $27.6 \pm 2.0 \text{ g kg}^{-1}$ (control group) in pine-dominated plots and from $26.8 \pm 3.4 \text{ g kg}^{-1}$ (control) to $27.3 \pm 2.2 \text{ g kg}^{-1}$ (fertilized) in spruce sample plots.

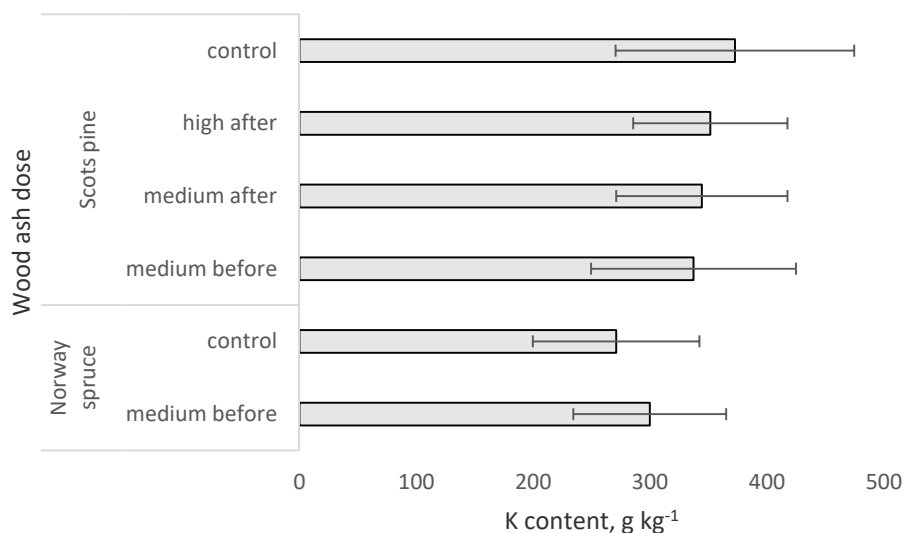


Figure 6. Content of potassium (K) in the soil 10 years after planting seedlings fertilized using different wood ash doses (5 to 10 t ha^{-1} = medium dose before planting seedlings, 5 to 10 t ha^{-1} = medium dose after planting seedlings, 15 to 20 t ha^{-1} = high doses after planting seedlings, and control = untreated plots, 0 t ha^{-1} ; SP: Scots pine, NS: Norway spruce; the confidence interval is represented by vertical error bars).

3.3. Growth of Fertilized Trees

Fertilization effects on pine seedling morphological parameters differed between applied wood ash doses and the control plot (Table 1). After one year, the plots where wood ash was applied a year before planting had higher values than the control plot in all analyzed parameters (seedling height, aboveground biomass, root mass, and root mass and plant mass proportions). The Scots pine height in the control plots was $15.2 \pm 0.3 \text{ cm}$. In plots where fertilization was carried out in medium doses before planting, the tree height was $15.8 \pm 0.4 \text{ cm}$. Overall, applying fertilizers in medium doses prior to planting pine seedlings has a positive effect on tree biomass growth.

Further, the analysis was applied to pine dominated plots where fertilization was done right after planting seedlings. No significant differences ($p > 0.05$) were observed for sample plots with medium to high doses after planting compared to control fields after one year of establishment (Table 1). Applying medium doses of wood ash after planting had lower results than in control fields where the tree height was $15.2 \pm 0.3 \text{ cm}$, but in plots with medium and high doses, the height was $14.9 \pm 0.3 \text{ cm}$. A similar trend was observed for aboveground biomass where the control plots had higher values than the medium to high dose sample plots.

Fertilization effects on spruce growth and biomass one year after establishing the experiment between control and sample plots were analyzed where the wood ash application was carried out a year before planting. The control plot had lower values in all analyzed parameters (aboveground biomass, root mass, and root mass/plant mass proportion), and the fertilization effects on root biomass

and root and plant mass proportion differed significantly between experimental plots, thus wood ash application improved seedling morphological development (Table 1).

Table 1. Pine and spruce seedling morphological parameters (mean value \pm standard deviation) one year after applying wood ash in various doses (5 to 10 t ha⁻¹ = medium before, 5 to 10 t ha⁻¹ = medium after, 15 to 20 t ha⁻¹ = high after, and 0 t ha⁻¹ = control) [10].

Variant	Tree Species	Seedling Height, cm	Aboveground Biomass, g	Root Mass, g	Root Mass % From Plant Mass
Control	Scots pine	15.2 \pm 0.3	3.11 \pm 0.13	1.19 \pm 0.05	27.7 \pm 0.6
Medium before	Scots pine	15.8 \pm 0.4 *	3.71 \pm 0.17 *	1.43 \pm 0.08 *	28.0 \pm 0.8
Medium after	Scots pine	14.9 \pm 0.3	2.90 \pm 0.11	1.26 \pm 0.06	30.2 \pm 0.7
High after	Scots pine	14.9 \pm 0.3	2.83 \pm 0.12	1.16 \pm 0.06	29.7 \pm 0.7
Medium before	Norway spruce	-	0.60 \pm 0.04 *	0.26 \pm 0.02 *	30.5 \pm 0.9 *
Control	Norway spruce	-	0.53 \pm 0.03	0.23 \pm 0.02	29.6 \pm 0.7

* indicates statistically significant differences ($p < 0.05$) between treatments [10].

Pine growth was not significantly affected by the amount of wood ash application after the stand establishment (planting); however, some tendencies were observed after a 10-year period (Figure 7). The application of ash one year prior to the planting had a positive effect on the height growth of pines (increasing from 3.8 \pm 0.4 m in the control plots to 4.4 \pm 0.6 m in the fertilized plots with a medium dose before planting), and the effect was not dependent on the dose of wood ash. The lowest height of trees (3.3 \pm 0.4 m) was monitored in plots where high doses of wood ash were applied after planting.

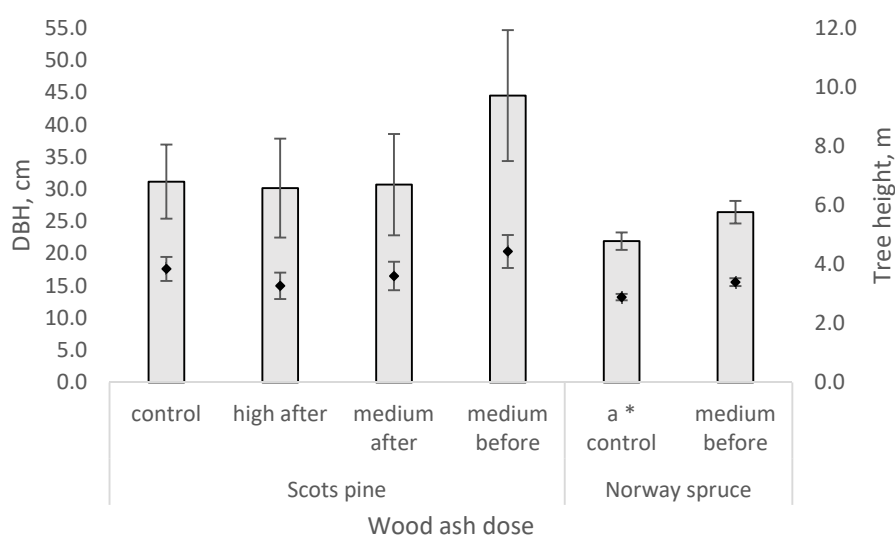


Figure 7. Mean diameter at breast height (DBH) and height of trees planted on sample plots using different wood ash fertilization doses (5 to 10 t ha⁻¹ = medium dose before planting seedlings, 5 to 10 t ha⁻¹ = medium dose after planting seedlings, 15 to 20 t ha⁻¹ = high dose after planting seedlings, and control = untreated plots, 0 t ha⁻¹; SP: Scots pine, NS: Norway spruce) 10 years after establishment (gray bars indicate DBH, black dot denotes tree height, and the confidence interval is represented by vertical error bars, * indicates significant differences of DBH between treatments, a—indicates significant height differences between treatments).

No significant DBH differences were observed for pine plots where the application of ash was done a year after, however the application of ash one year before planting had noticeable positive effect on pine radial growth (Figure 7). The tree DBH for control fields was 31.2 \pm 5.8 mm, but for plots fertilized prior to planting, the DBH was 44.5 \pm 10.2 mm. Other fertilized plots exhibited rather similar

results, yet lower values than those of the control fields. Overall, applying wood ash one year before planting seedlings demonstrates a noticeably higher but non-significant difference in tree height and DBH in comparison to any other sample field.

Wood ash application has significantly positive ($p < 0.05$) effects on the spruce height and diameter growth after 10 years for wood ash application in comparison to the control treatment (Figure 7). The DBH for the control plot after 10 years was 21.9 ± 1.4 mm, whereas in the fertilized sample plots, the DBH increased to 26.40 ± 1.8 mm. In addition, the height increment also differed significantly between sample plots. The tree height in the control plot was 2.9 ± 0.11 m, but in the fertilized plots, the height reached 3.4 ± 0.13 m.

3.4. Dead Standing Tree Parameters

Scots pine height of alive trees in sample plots ranged from 1.45 to 5.08 m, 1.3 to 6.03 m, 1.2 to 6.65 m and 1.59 to 5.41 m in control plots, plots fertilized prior planting, plots fertilized after planting with medium doses and plots fertilized with high doses, respectively. In spruce sample plots, the tree height of alive trees ranged from 1.25 to 4.43 m and 0.64 to 5.03 m in control and fertilized plots, respectively.

After 10 years, the average height of dead standing trees in spruce sample plots was 1.75 ± 0.31 m and 1.63 ± 0.1 m in control and fertilized plots, respectively. In pine dominated plots, the average height of dead standing trees was 1.46 ± 0.05 m, 1.74 ± 0.39 m in control and plots fertilized prior to planting, respectively. In pine sample plots where wood ash was applied after planting the seedlings in medium and high doses, the average tree height was 2.13 ± 0.31 m and 2.52 ± 0.57 m, respectively.

4. Discussion

Wood ash chemical content used in our experiment was average compared to chemical content used in other fertilization studies (Table 2). Soil chemical content of different wood ash application doses is summarized in Supplementary Material (Table S1).

Table 2. Chemical content of wood ash used for the experiment, %.

Elements	Wood Ash Chemical Content, % [10]	Range of Wood Ash Chemical Content in Other Studies, % [32,33]
Phosphorus (P)	0.92	0.3–1.4
Potassium (K)	2.30	1.4–4.2
Calcium (Ca)	22.0	7.4–33.1
Magnesium (Mg)	1.50	0.7–2.2
Silicon (S)	0.38	0.4–0.7
Iron (Fe)	0.39	0.3–2.1
Manganese (Mn)	0.67	0.3–1.3
Zinc (Zn)	0.11	0.0004–0.0820
Copper (Cu)	0.0054	0.0052–0.0289
Molybdenum (Mo)	0.000125	
Boron (B)	0.0158	0.0022–0.0225
Sodium (Na)	0.093	

Some of the most prominent effects of wood ash application are the decreased soil acidity, and increased mineralization rate of forest soil [8]. Some of the elements in wood ash are quickly leached into the soil, for example, content of K can be found in the soil at deeper levels shortly after the application of ash [9]. In our study, the content of K between the control and experimental plots differed substantially, as the wood ash treatment increased the soil K content up to six times in plots with high doses (Figure 2). Similar results have been reported in Finland, where wood ash fertilization already

had a positive effect on potassium deficit decrease in soil one year after ash application [19]. However, the lowest K content in the soil was found for plots (excluding control plots) where the wood ash was applied a year before planting, which demonstrates the quick K infiltration process. Such an increase in K content in the soil testifies to the lack of availability of this element for trees, as presumably, K can be a limiting factor for growth in the sample fields. No significant differences were observed for spruce-dominated sample plots. After 10 years, the differences were not as pronounced, as the K content in the soil was similar in all the study plots (Figure 6).

On drained peatlands the availability of P and K limits tree growth; therefore, a significant increase in needle mass and content of both macronutrients in the soil can be observed in the wood ash fertilized stands after a long period [19]. In this experiment, after one year, the content of P increased significantly in pine-dominated plots where ash was used after planting seedlings. More wood ash resulted in a higher content (Figure 3); such results have also been reported by I. Stupak [8]. Even with an ash application with high doses, no significant differences were observed after the 10-year period (Figure 5). For spruce-dominated plots, the P content in the fertilized plots increased noticeably in comparison to the control plots, and the differences can be observed even after 10 years; however, the differences were not statistically significant.

Fertilization experiments in Nordic countries performed in Scots pine stands showed that N was the only element that demonstrated a significant effect on tree growth [34]. However, the soil in the study site was N rich; therefore, additional macronutrients for growth were not added, except the wood ash which is rich in P, K, and other micronutrient elements (Table 1). The N content in the soil at one and 10 years after the wood ash application did not statistically significantly differ between tree species or wood ash doses (Figure 4). Trees use N in their growth processes; therefore, the N content decreases after planting seedlings, but the application of wood ash initiates the decomposition of organic soil [15,18,35]. A higher content of N in the soil after fertilization with wood ash was observed, and plants use it for their metabolic processes. The obtained tree biomass could be a result of the decomposition of organic soil; however, after 10 years, these processes slow down.

Tree height and DBH 10 years after wood ash fertilization did not exhibit big differences for plots where fertilization was applied after planting the seedlings. However, in plots where fertilization was done before planting, the tree height and DBH were larger compared to the control fields (Figure 7). Height and DBH in the fertilized spruce sample plots were significantly higher than in the control fields. Applying fertilizers before planting lets the macronutrients leach into the soil, which made it easier for spruce seedlings to absorb these elements efficiently right after planting. Our findings are in accordance with previous studies, where the initial fertilization effect can significantly increase tree dimensions up to 15 years after fertilizer application [36].

High doses of wood ash fertilizer did not result in an increase in tree height or DBH for Scots pine. The study results showed rather similar average height values compared to the control plots. The height of the trees was the lowest in plots where the most wood ash was used and was the highest in fields where fertilization was done before planting the seedlings (Figure 7). Similar results have been reported in previous studies where high doses (up to 20 t ha⁻¹) of wood ash were not found to be toxic or cause significantly lower growth parameters for trees [37,38]. Therefore, a limiting factor for growth might be other nutrients that are not applied with the wood ash. Most often in studies, the addition of N is recorded as the only treatment, which can provide a significant tree biomass increase on mineral soils [6]. Furthermore, studies from Estonia, where young Scots pines growing on mineral soils were examined, showed no significant differences in the height and radial growth of trees on plots treated with 2.5 to 5 t ha⁻¹ of wood ash [39], but an increase occurred after the application of 3 t ha⁻¹ with 150 kg ha⁻¹ of N [22]. Therefore, the role of N in the soil is an important factor. However, as mentioned, in the current study, the N content in the soil was sufficient, and no significant differences between sample plots were observed (Figure 4).

From the economic point of view, the transportation and mechanized spreading of wood ash are expensive processes. The initial fertilization is a technically simpler method than the application of

fertilizer after planting and later before thinning the trees. Therefore, applying wood ash fertilizer in higher intensity prior planting could be practiced in forest management. The application of high doses of wood ash, despite their high expenses, did not improve pine growth more than in other fertilized plots. Wood ash application in different doses prior planting had a positive influence on spruce growth parameters. Soil properties increased in all plots where ash was used; thus, on peatlands, fertilization can increase P and K content even in high doses. Therefore, it is economically acceptable to use lower doses of ash but apply them before planting seedlings because spruce sample plots exhibit better results than control plots. In contrast, the application of wood ash did not cause increased decaying or mortality. The mortality could be explained with species competition, as the average height of dead standing tree was low (close to minimal tree height in the sample plot). Therefore, the analyzed wood ash does not have a significant negative influence on tree growth even with high doses.

5. Conclusions

Wood ash is a long-term fertilizer and liming material with a significant effect on P and K content in the soil of pine-dominated plots in the first year after application of wood ash. The effect of fertilization is still present in the soil even 10 years after planting the seedlings. Using fertilizers in medium doses (5 to 10 t ha⁻¹) a year prior to planting increases tree biomass in the short term and significantly increases the tree height and DBH in the long term in spruce stands compared to the control plots. In plots where the same amount of wood ash (5 to 10 t ha⁻¹) was applied after seedlings were planted, the results of the tree height and DBH are similar or lower compared to the control plots. High doses of wood ash have growth parameters that are similar to the control plots, but despite the higher content of soil macronutrient elements, high doses of wood ash do not seem to reach the overdose limit. Therefore, an economically acceptable and sustainable management option for wood ash application would be to apply medium doses of wood ash a year prior to planting rather than using high doses.

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