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Title:	Effects of wood ash, nitrogen, and biosolids fertilisation on the growth and soil properties of Scots pine and Norway spruce stands
Year:	2025
Version:	Published version
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Please cite the original version:

Harri Mäkinen, Hannu Ilvesniemi, Antti-Jussi Lindroos, Aino Smolander, Effects of wood ash, nitrogen, and biosolids fertilisation on the growth and soil properties of Scots pine and Norway spruce stands, Forest Ecology and Management, Volume 578, 2025, 122467, ISSN 0378-1127, https://doi.org/10.1016/j.foreco.2024.122467. .

Forest Ecology and Management 578 (2025) 122467

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Effects of wood ash, nitrogen, and biosolids fertilisation on the growth and soil properties of Scots pine and Norway spruce stands

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ARTICLE INFO

Keywords:
Ash
Biosolids
Fertilisation
Forest growth
Nitrogen
Soil properties

ABSTRACT

The recycling of wood ash back to forests has the potential to restore nutrients that are removed during the harvesting of wood chips for bioenergy. Biosolids are nutrient-rich organic residual materials derived from biowaste and sewage sludge with potential use as fertiliser. The objective of this study was to assess the impact of wood ash fertilisation, with and without nitrogen (N) addition, as well as biosolids addition, on forest growth, and soil properties and processes. The material was collected from fertilisation experiments in southern Finland, two in Scots pine (*Pinus sylvestris* L.) stands and four in Norway spruce (*Picea abies* (L.) Karst.) stands on mineral soil, approximately 10 years after the treatments were applied. The treatments were as follows: a control with no fertilisation, two doses of wood ash (3000 kg ha^{-1}, and 9000 kg ha^{-1}), a nitrogen addition (180 kg ha^{-1}), and treatments with N and ash additions. In addition, biosolids (4400 kg ha^{-1}) were applied. The treatments had only a slight impact on growth in both pine and spruce stands. The most notable impact on the chemical properties of the humus layer was a reduction in acidity and an increase in base cation concentrations on the plots fertilised with ash. Conversely, the addition of N and/or wood ash did not result in a consistent impact on the C-to-N ratio, rates of carbon and net N mineralisation, or carbon and N amounts. The limited growth response to the N addition in any form is attributable to the minor alteration in N availability. Furthermore, the application of wood ash and biosolids did not result in any discernible adverse effects on soil properties.

1. Introduction

Nitrogen (N) is often the primary nutrient that constrains the growth of boreal forests on mineral soils (Binkley and Högberg, 2016; Högberg et al., 2017). The use of inorganic fertilisers to provide N to trees and to increase forest growth is a long-established practice in the Nordic countries (Saarsalmi and Mälkonen, 2001; Prietzel et al., 2008; Saarsalmi et al., 2014b). A single application of N fertiliser at a rate of 150 kg N ha^{-1} has typically resulted in an increase in stand growth of 6 %–20 % over a period of 7–10 years (Kukkola and Saramäki, 1983; Nohrstedt, 2001). The addition of N has been demonstrated to exert an increasing effect on soil carbon (C) stocks across a range of forest ecosystems (Mayer et al., 2020). Similarly, numerous studies have demonstrated that N addition has resulted in a notable increase in soil C stock across of a multitude of Nordic forest (Högberg, 2007; Saarsalmi et al., 2014b; Maaroufi et al., 2015).

The addition of fast-release N fertilisers to forest soils has stimulated the mineralisation of soil organic N reserves, but simultaneously generally decreased the mineralisation of C, microbial biomass C and N, and the fungal-to-bacterial biomass ratio, with a particular impact on mycorrhizal fungi (Smolander et al., 1994, 1995; Treseder, 2008; Maaroufi et al., 2019). One of the primary factors contributing to the reduction in C mineralisation is the inhibition of lignin-degrading enzymes (Chen et al., 2018). The larger soil C stock resulting from N addition (Högberg, 2007; Saarsalmi et al., 2014b; Maaroufi et al., 2015) can be attributed to two factors: increased above- and below-ground litter input and decreased mineralisation of C (Marshall et al., 2021).

The utilisation of forest-based biomass for bioenergy production is increasing, driven by the necessity to reduce reliance on fossil fuels and achieve carbon neutrality targets. The utilisation of forest primary

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https://doi.org/10.1016/j.foreco.2024.122467
Received 2 October 2024; Received in revised form 4 December 2024; Accepted 9 December 2024

Table 1
The locations and characteristics (± standard deviations) of the experiments at the time of establishment.

Experiment	Latitude	Longitude	Altitude, m	Site type*	Soil texture	Tree species	Age	No stems ha^{-1}	Basal area, m^2ha^{-1}	Height, m **	Site index, H_{100}
Heinola (814)	61°16’	25°95’	140	VT	coarse-grained till	pine	51	853 ± 61	15.9 ± 2.4	12.1 ± 1.0	26.4
Loppi (816)	60°68’	24°07’	142	VT	coarse-grained till	pine	41	792 ± 132	13.6 ± 1.3	12.4 ± 1.1	29.3
Karkkila (812)	60°58’	24°26’	133	MT	fine-grained till	spruce	47	693 ± 99	19.9 ± 2.0	17.8 ± 0.6	34.7
Loppi (815)	60°68’	24°07’	142	MT	coarse-grained till	spruce	41	865 ± 123	15.2 ± 2.7	14.9 ± 1.8	34.0
Hartola (817)	61°65’	26°29’	147	MT	fine-grained till	spruce	42	960 ± 185	15.7 ± 1.7	13.2 ± 1.0	32.5
Jämsä (819)	61°88’	24°89’	181	MT	fine-grained till	spruce	51	761 ± 85	22.6 ± 2.1	18.8 ± 1.0	34.2

[*] Site types (Cajander, 1949): VT, *Vaccinium vitis-idea*; MT, *V. myrtillus*

[**] Tree basal area weighted mean height

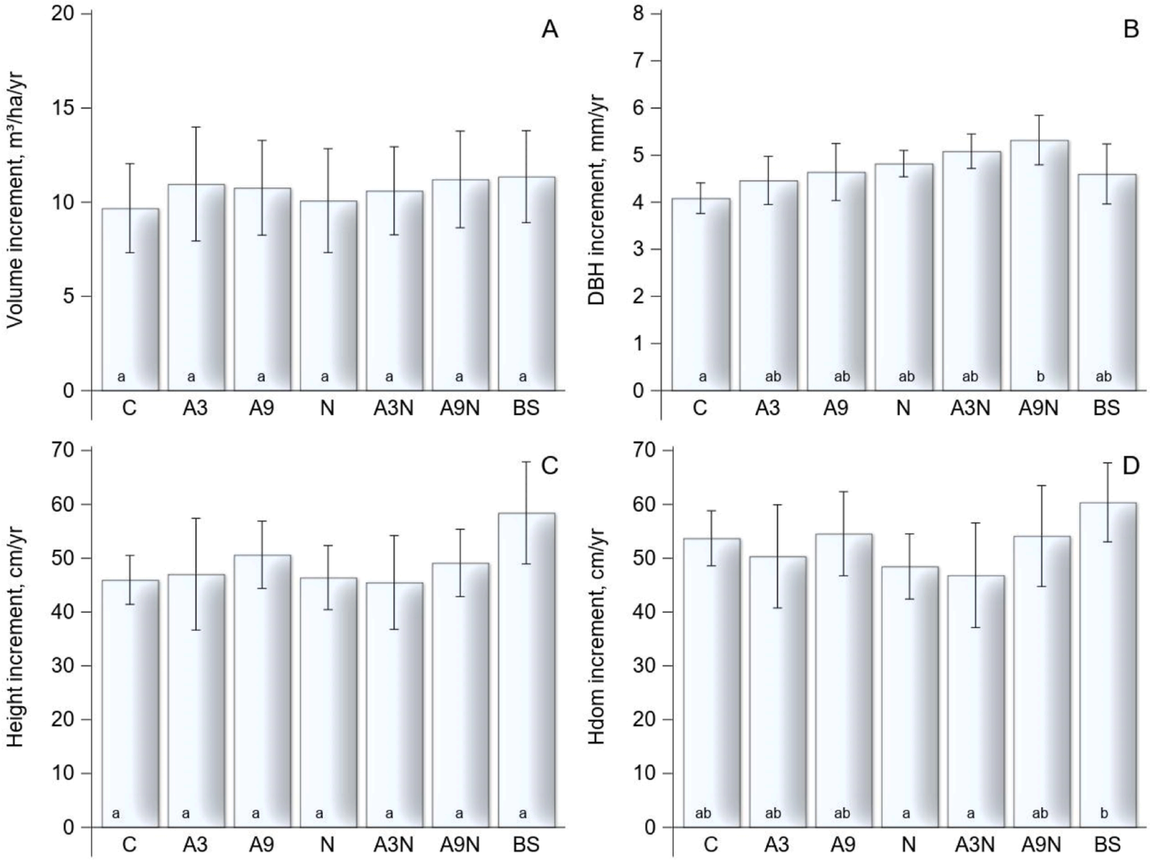

Fig. 1. The mean annual stem volume increment, basal area-weighted diameter and height increment, and dominant height increment of the Scots pine experiments. The treatments were as follows: control (C), wood ash at 3000 kg ha^{-1} and 9000 kg ha^{-1} (A3, A9), nitrogen (N), two doses of wood ash with nitrogen (A3N, A9N), and biosolids (BS). Treatments marked with the same letter are not significantly different ($p < 0.1$). The error bars represent standard deviation. The number of plots in each treatment was 3–4.

biomass, particularly the harvesting of logging residues, increases nutrient removal and soil acidification, in addition to alterations in soil C and N cycling and pools. This is due to changes in the composition of organic matter and a reduction in the mineralisation of C and N (Olsson et al., 1996; Smolander et al., 2010, 2013; Clarke et al., 2021). Conversely, the increasing conversion of forest chips and forest industry sidestreams into energy increases production of wood ash. The recycling of wood ash back to forests may prove an efficacious method of restoring nutrients removed during logging and harvesting of wood chips, while also reducing soil acidity (Rosenberg and Jacobson, 2004). Wood ash contains all the major mineral nutrients, with the exception of N, including base cations (Ca, Mg, and K), phosphorus (P), and boron (B). However, these are not typically the limiting nutrients for tree growth on mineral soils in boreal forests (Saarsalmi and Tamminen, 2005). The application of ash as a fertiliser results in a sustained reduction in soil acidity due to the high Ca content of the ash (Jacobson et al., 2004; Saarsalmi et al., 2006, 2012). Wood ash fertilisation is particularly beneficial on peatland sites, where a lack of P and K are the main nutrients limiting tree growth (Ludwig et al., 2002; Moilanen et al., 2002). On N-poor mineral soils, ash fertilisation has not increased stand growth, and in some cases, it has led to a slight decrease in growth (Saarsalmi et al., 2004). Notwithstanding the absence of N in wood ash,

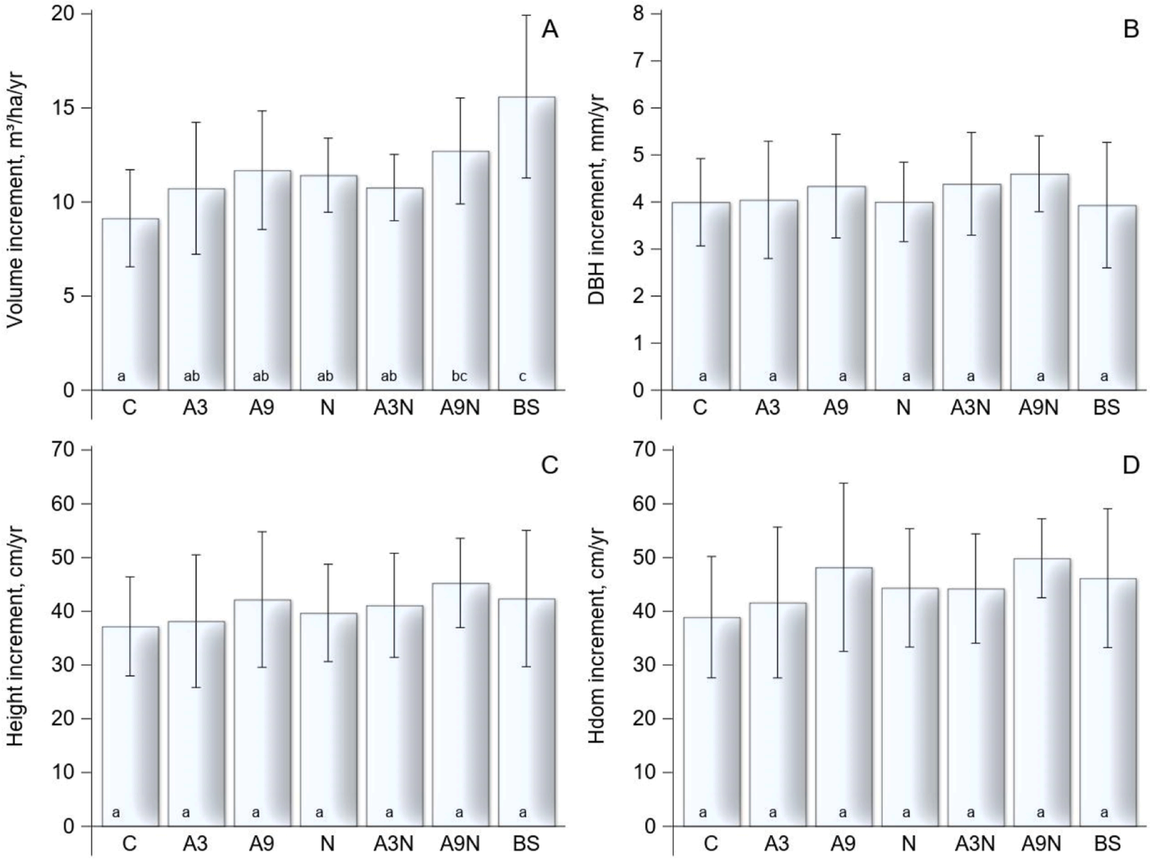

Fig. 2. The mean annual stem volume increment, basal area-weighted diameter and height increment, and dominant height increment of the Norway spruce experiments. The treatments were as follows: control (C), wood ash at 3000 kg ha^{-1} and 9000 kg ha^{-1} (A3, A9), nitrogen (N), two doses of wood ash with nitrogen (A3N, A9N), and biosolids (BS). Treatments marked with the same letter are not significantly different ($p < 0.1$). The error bars represent standard deviation. The number of plots in each treatment was 5–8.

it has stimulated soil microbial activity, litter and cellulose decomposition, and the mineralisation of soil organic N reserves (Perkiömäki and Fritze, 2005; Rosenberg et al., 2010; Saarsalmi et al., 2012). This may result in an increase in the availability of N. Consequently, ash fertilisation has notably increased the growth of Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) stands in southern Sweden (Jacobson, 2003). In a meta-analysis conducted in managed forests of Europe and North America, Reid and Watmough (2014) found that the addition of wood ash increased tree growth in 33 % of the experiments. They concluded that initial soil pH, tree species and length of monitoring period had a significant impact on the growth response.

The combined impact of wood ash and N addition on stand growth has been observed to vary (Huotari et al., 2015). Saarsalmi et al. (2010) observed that ash addition did not result in any additional growth response. Some studies have indicated that wood ash can even reduce the growth response to N addition (Pettersson, 1990). Conversely, a positive long-term growth response to the combined ash and N addition was identified in coniferous stands on nutrient-poor mineral soil sites (Saarsalmi et al., 2006, 2012, 2014a). Furthermore, the combined addition of ash and N resulted in a long-term stimulation of net N mineralisation in the humus layer of some of the same sites, which was detectable even 20–30 years after the addition (Saarsalmi et al., 2010, 2012, 2014a).

The utilisation of organic materials is regarded as a potential means of enhancing soil properties and tree growth through the provision of nutrients. Biosolids are organic residual materials resulting from the treatment of sewage sludge. They can be provided in a variety of forms, including liquid and solid pellets, and are treated in order to meet the relevant microbiological and chemical standards. The recycling of biosolids to forest stands has been demonstrated to increase tree growth. This is due to the fact that biosolids are rich in organic matter and nutrients (Bramryd, 2002, 2013; Wang et al., 2017). Notwithstanding the long-standing utilisation of biosolids on agricultural lands, the deployment of biosolids on forest lands is proscribed in a number of countries, including Finland, as a consequence of environmental concerns. The environmental concerns associated with biosolids include the presence of heavy metals, organic contaminants (including antibiotics), nitrate leaching, pathogens, odour generation, and public perception (Scharenbroch et al., 2013). Consequently, there is a paucity of knowledge regarding the effects of biosolids on forest soil properties, particularly in comparison to research on agricultural soils. It is therefore unclear whether biosolids can be used without causing significant detrimental changes to soil properties. Furthermore, there is still much to be learned about the impact of biosolids application on forest growth.

The objective of this study was to assess the impact of wood ash fertilisation, with and without N addition, as well as biosolids addition, on the growth of Scots pine on relatively infertile sites and Norway spruce stands of medium fertility. Furthermore, we aimed to evaluate whether the diverse fertilisers and their combinations exert consistent effects on soil properties and processes, and whether they provide explanations for the growth responses observed in response to the treatments. We hypothesised that the application of wood ash to relatively infertile sites would have no impact on stand growth. Nevertheless, we expected that the addition of ash addition would lead to a slight increase in growth on sites of medium fertility. Similarly, we hypothesised that the addition of N, with or without wood ash, would stimulate growth irrespective of site fertility, as would the addition of biosolids. Moreover, we hypothesised that the treatments would induce changes in the

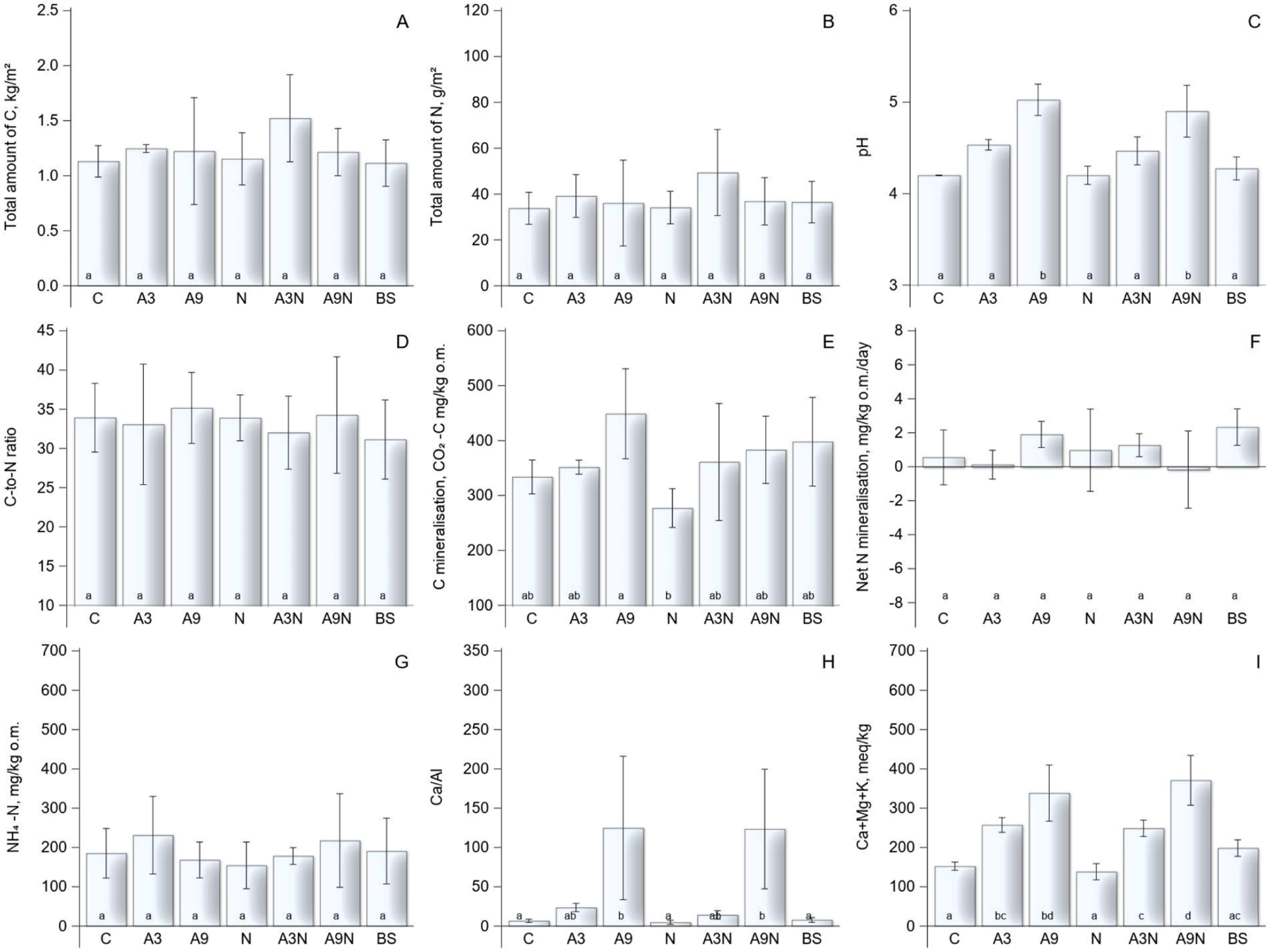

Fig. 3. The properties of the humus layer in the Scots pine experiments. The treatments were as follows: control (C), wood ash at 3000 kg ha^{-1} and 9000 kg ha^{-1} (A3, A9), nitrogen (N), two doses of wood ash with nitrogen (A3N, A9N), and biosolids (BS). Treatments marked with the same letter are not significantly different ($p < 0.1$). The error bars represent standard deviation.

amount of N in the soil that could be linked to growth responses.

2. Material and methods

2.1. Study sites and treatments

The material was gathered from six fertilisation experiments conducted in southern Finland, comprising two experiments in pure Scots pine and four experiments in pure Norway spruce stands (Table 1). The pine experiments were conducted on sub-xeric sites (i.e., relatively infertile sites, designated VT according to the Finnish site classification system, Cajander, 1949), while the spruce experiments were carried out on mesic heath sites (i.e., medium-fertile sites, designated MT, Cajander, 1949). The soil type was identified as podzol, and the humus layer was classified as mor (IUSS Working Group WRB, 2007).

The experiments were established to relatively dense, well-managed stands at the first thinning phase. At the time of establishment between 2009 and 2011, the stands were thinned from below in accordance with the recommendations in the forestry practice guidelines (Rantala, 2011). Following the thinning, the remaining number of stems ranged from 761 stems ha^{-1} to 960 stems ha^{-1}. The method employed was whole-tree harvesting, whereby all the above-ground biomass was removed, leaving no logging residues on the stands.

The treatments were as follows: a control with no ash or N addition (C), two doses of wood ash (3000 kg ha^{-1} (A3), and 9000 kg ha^{-1} (A9)), a N addition (180 kg ha^{-1} as ammonium nitrate, ammonium (54 %) and nitrate (46 %)) (N), and treatments with N (180 kg ha^{-1}) and ash additions (A3N and A9N). The granulated ash (for the composition, see Supplementary Material, Table S1) was derived from wood fuel and was produced at a thermal plant (supplier FA Forest Ltd.). The fertilisers were applied manually in the spring following the thinning, and the treatments were replicated twice in each experiment as randomised blocks, i.e., a total of 12 plots per stand. The plots were 25 m × 25 m in size and surrounded by a 10 m wide buffer zone, which was treated in the same manner.

In 2013, two further plots were established for each experiment, comprising biosolids (BS). The biosolids were produced by Lakeuden Etappi Ltd. derived from biowaste and sewage sludge originating from a municipal wastewater treatment plant in southern Finland. The substance has been approved for use as a fertiliser in agriculture in Finland. The anaerobically putrefied, dewatered and pelletised biosolids were applied at a rate of 4400 kg ha^{-1}, which is equivalent to 150 kg N ha^{-1} (including C 285 g kg^{-1}, for the composition, see Supplementary Material, Table S1). The biosolids pellets were distributed manually across the plots, with no additional fertiliser applied beyond the biosolids treatment. In Experiment 819, the limited space available precluded the establishment of new plots, necessitating the distribution of the biosolids to the existing control plots. As a result, the experiment lacked a control treatment.

Severe wind damage occurred on plots A9 and BS in Experiment 812,

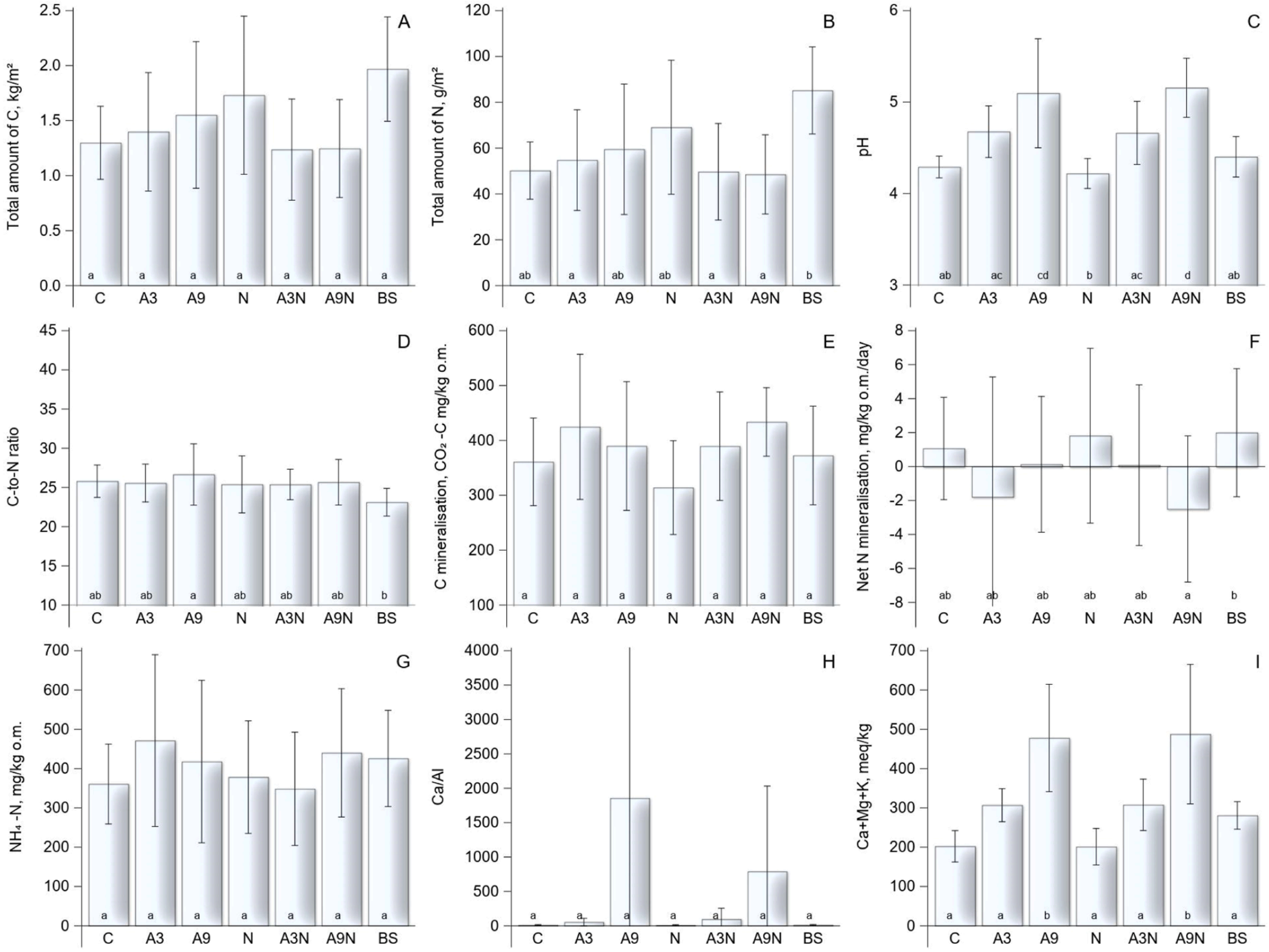

Fig. 4. The properties of the humus layer in the Norway spruce experiments. The treatments were as follows: control (C), wood ash at 3000 kg ha^{-1} and 9000 kg ha^{-1} (A3, A9), nitrogen (N), two doses of wood ash with nitrogen (A3N, A9N), and biosolids (BS). Treatments marked with the same letter are not significantly different ($p < 0.1$). The error bars represent standard deviation.

on plots C and N in Experiment 815, and on plots C, A9, A3N and A9N in Experiment 816. As a result, these plots were excluded from the subsequent analyses; the aforementioned treatments were represented by a single plot in each of the affected experiments.

2.2. Stand measurements

The experiments were measured for the first time at the establishment between 2009 and 2011, and the biosolids plots in 2013. Subsequent measurements were conducted in the autumn of 2020. The diameter of all stems at breast height (1.3 m) were recorded. Tree height and crown base height were measured on a randomly selected sample of trees, with approximately 20–40 trees on each plot. The heights of the remaining trees were estimated using Näslund's height curve (Näslund, 1937), which was calibrated for each plot based on the heights of the sample trees. Based on the sample tree measurements and predicted heights, the dominant height was calculated for each plot, defined as the mean height of the 100 thickest trees ha^{-1}. Stem volume of each tree was calculated using volume functions based on the stem diameter and tree height (Laasasenaho, 1982).

The stand and tree characteristics were calculated from sample measurements using the KPL software developed at the Finnish Forest Research Institute (Heinonen, 1994). Given the slight disparity in the measurement period lengths between the experiments and plots, the annual increments were calculated as the difference between the final and initial measurements, divided by the number of years between the measurements. Site indices (H_{100}, defined as the dominant height at age 100 years in metres) were calculated using the equations by Vuokila and Väliaho (1980).

2.3. Soil sampling and chemical analyses

The impact of various fertiliser applications on soil properties and processes was assessed through the examination of the samples taken from the humus layer in August 2022. A total of twenty soil cores were systematically collected from each plot using a soil auger with a diameter of 58 mm. The thickness of the humus layer (F+H, i.e., fermented and humic layers) was quantified and it was subsequently separated from the litter and mineral soil layers. The samples of the humus layer were combined to create a single composite sample for each plot. The composite samples were transported to the laboratory in plastic bags within a cold box and stored at −18 °C prior to further processing.

The samples were melted at a temperature of + 4°C prior homogenisation by sieving through a 6.8 mm mesh size sieve. Subsequently, the sieved samples were weighed, and a portion of the sieved samples was used as a fresh sample, while a portion was air-dried 48 h at 60°C. The dry matter content, organic matter content, and soil water holding capacity (WHC) were determined in accordance with the methodology

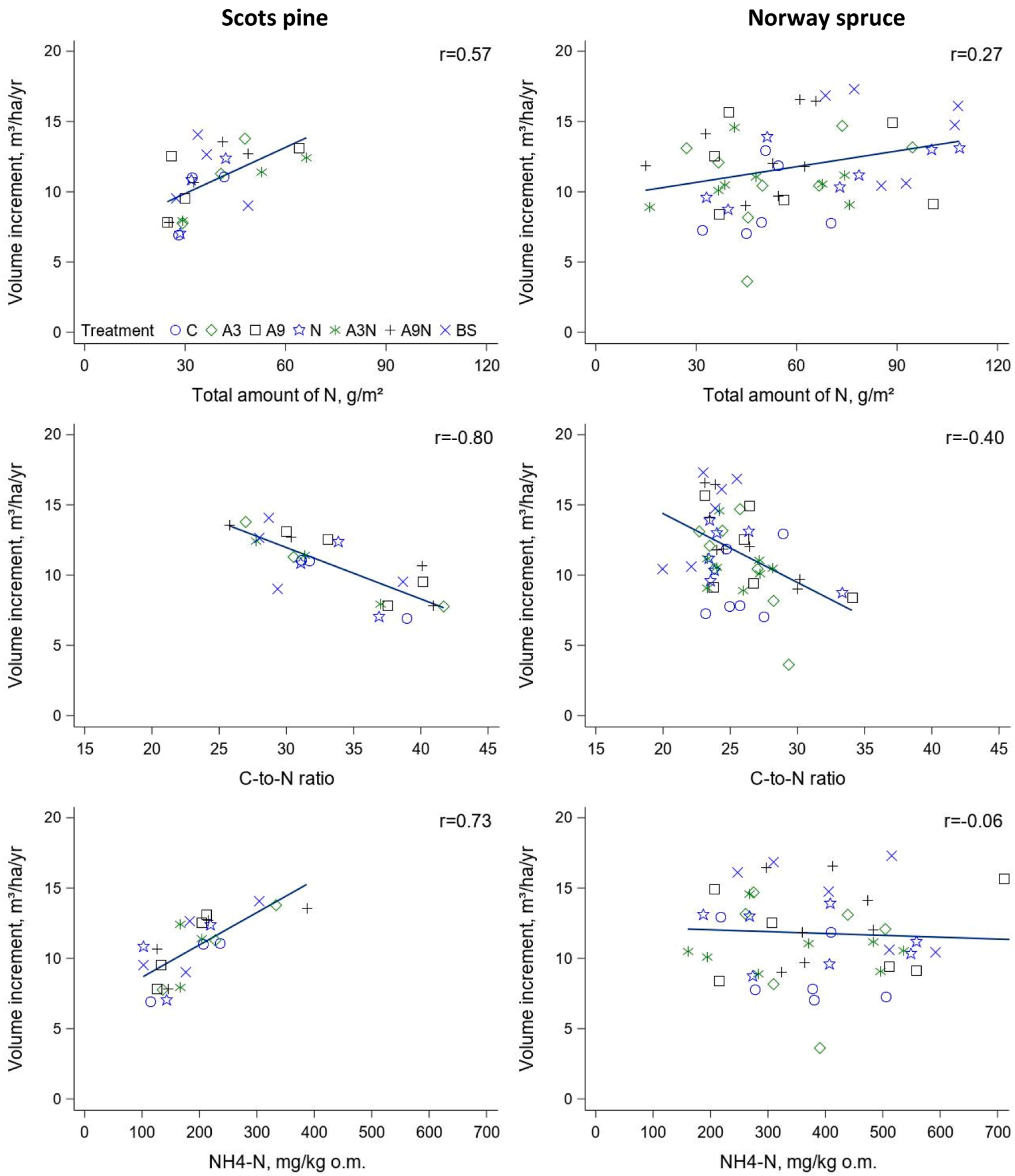

Fig. 5. The volume increment and properties of the humus layer, as well as their correlations, in the Scots pine (left column) and Norway spruce (right column) experiments. All correlations were statistically significant ($p < 0.10$), except the correlation with NH_4-N for spruce.

described by Soronen et al. (2024).

From the fresh homogenised samples, the rates of net N mineralisation, net nitrification and C mineralisation were measured in a four-week incubation experiment at constant moisture (WHC 60 %) and at the average soil temperature during the summer months (14°C, Törmänen et al., 2018), as previously described by Soronen et al. (2024). In brief, the net mineralisation of N and net nitrification were determined, after KCl extraction, as accumulation of (NH_4+NO_3)-N or NO_3-N, respectively, during the incubation period. The aerobic mineralisation of C was estimated by measuring the rate of CO_2-C production. This was achieved by closing the incubation bottles with gas-tight septa 20 hours prior to the measurement of the produced CO_2 by gas chromatography. The measurement was performed twice during the four-week incubation, approximately one and two weeks after the commencement of the incubation.

The total C and N contents of the sieved and dried humus layer samples were determined by dry combustion with a CHN analyser, as detailed by Soronen et al. (2024). The presence of carbonates is almost non-existent in Finnish forest soils, which lends support to the assumption that the total C content is comprised entirely of organic carbon. The weight of the sieved, dry soil was related to the area of the 20 cores, thus enabling the estimation of the C and N amounts per unit area. The $pH(H_2O)$ of the samples was determined. Exchangeable cations and nutrients were determined through extraction with $BaCl_2$, and the element concentrations were determined from the extract by inductively coupled plasma atomic emission spectrophotometer (ICP/AES) (Cools and De Vos, 2020).

2.4. Statistical analyses

The statistical significance of the differences in the stand characteristics and soil properties among the treatments was evaluated using a mixed model analysis with the Mixed procedure of SAS, version 9.4 (SAS Institute Inc, 2023). The model included a fixed effect for the treatments and the experiments, as well as a continuous covariate measured at the establishment of the plots. The covariate was dependent on the variable under analysis, included stand basal area, tree basal area weighted mean stem diameter, tree basal area weighted mean height, or dominant height. In the case of soil properties, the pretreatment values were not available, and thus no covariate was employed. Furthermore, the models incorporated random effects for the blocks within the experiments; however, these were excluded as the majority of models incorporating random block effects failed to converge. Pairwise comparisons were conducted by computing generalised least-squared means of the treatment effects. The adjusted *P*-values for the multiple comparison were calculated using the simulated distribution of the maximum or minimum value of a multivariate *t* random vector. A value of $p < 0.1$ was considered deemed to indicate a statistically significant difference.

3. Results

3.1. Growth responses

The results of the pine experiments demonstrated that the treatments did not yield statistically significant differences in volume and height increment (Fig. 1). Accordingly, only some of the differences in the stem diameter increment and dominant height increment were statistically significant, due to the high degree of variation observed within and between the plots and experiments.

The spruce experiments yielded no statistically significant differences between the treatments with regard to stem diameter, height, and dominant height increment (Fig. 2). Conversely, the plots with the highest ash dose in conjunction with the N addition (A9N), along with the BS plots, exhibited the greatest volume increment, and these differed significantly from the control plots.

3.2. Soil responses

A number of soil variables exhibited inconsistencies between the pine and spruce experiments. For instance, the average C-to-N ratio was approximately 25 in the spruce experiments and nearly 35 in the pine experiments (Figs. 3 and 4). Additionally, the soil samples from the spruce experiments displayed lower acidity and higher concentrations of NH_4-N and base cations than those from the pine experiments (Figs. 3, 4, S1 and S2).

The treatments resulted in only minor differences in the total amount of N and in the amount of ammonium-N (NH_4-N), as well as in the total amount of C and the C-to-N ratio, in the humus layer (Figs. 3 and 4). The variation in the net N mineralisation rate between the sites was considerable for both tree species, with the average rate exhibiting negative values on a few wood ash plots. This suggests that during the incubation period, more N was immobilised than released. The rate of net nitrification and the amount of nitrate-N were both below the detection limit in all treatments.

The ash treatments, with and without N addition, clearly reduced soil acidity in both tree species, with the greatest reduction occurring at the highest ash dose (Figs. 3 and 4). Additionally, the N addition appeared to inhibit the mineralisation of C within the humus layer. However, the combined addition of N and ash eliminated this effect both in both pine and spruce.

The calcium/aluminium (Ca/Al) ratio, which indicates the deleterious effects of elevated Al and depressed Ca levels on soil acidity, exhibited a marked increase following the addition of ash, particularly when the dose of ash was high (Figs. 3 and 4). When examined individually, the concentration of Ca and Al exhibited contrasting trends in response to the varying ash treatments, i.e., the amount of Al decreased, while that of Ca increased with increasing amount of ash addition (Figs. S1 and S2). Moreover, the concentrations of Al and Ca on the BS plots were at the same level as those observed on the other plots without ash addition. However, the concentration of iron (Fe) was the highest on the BS plots among all the treatments (Figs. S1 and S2). Furthermore, the sum of equivalent-based concentrations of base cations (Ca+Mg+K) increased with increasing amount of ash addition in both tree species (Figs. 3 and 4).

3.3. Growth and soil nitrogen

In the pine experiments, a distinct positive correlation was identified between the volume increment and the total amount of N present in the humus layer. In contrast, the correlation between the volume increment and the amount of N was less pronounced in the spruce experiments (Fig. 5). Consequently, the relationship between the volume increment and the C-to-N ratio, as well as between the volume increment and the amount of ammonium-N, was more pronounced in the pine experiments. Moreover, no correlation was discerned between the volume increment and the amount of ammonium-N in the spruce experiments.

4. Discussion

The fertilisation treatments yielded only minor differences in stand growth, both in pine and spruce stands. In contrast with our hypothesis, the N addition did not result in a notable increase in growth, whether applied as a standard forest fertiliser or as biosolids. In contrast, the results support the hypothesis that wood ash addition has a negligible effect on stand growth. The most evident response of the chemical properties within the humus layer was a reduction in acidity and an increase in base cation concentrations on the plots that had been fertilised with ash, with the greatest effect observed at the highest dose. Otherwise, the impact of single N and/or wood ash applications on soil properties was found to be minimal.

The evidence from boreal conifer forests indicates that the addition of N has a positive effect on forest growth (e.g., Saarsalmi and Mälkonen, 2001; Prietzel et al., 2008; Högberg et al., 2017). The findings of this study diverge from the aforementioned general conclusions, and indicating that the N addition does not consistently elicit a significant growth increase. The sole noteworthy difference between the control plots and the fertilised plots was the higher volume increment observed on the biosolids plots for spruce. However, the BS treatment did not result in an increase in the diameter and height increment of those plots. There was a tendency for the stand density on the spruce BS plots to be somewhat higher than that on the other plots. It can therefore be surmised that the higher volume increment is probably caused by higher density. The effect of stand basal area as a covariate in the analysis did not fully remove this, as shown by the results.

The application of biosolids has been demonstrated to enhance tree nutrition, particularly the availability of N and phosphorus, while simultaneously increasing forest growth on acid and low-fertility soils (Wang et al., 2004; Scharenbroch et al., 2013; Ouimet et al., 2015). For example, Harrison et al. (2002) found that the application of municipal biosolids resulted in a 32 % increase in the volume growth of young Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) stands per hectare. Accordingly, Prescott and Blevins (2005) demonstrated that biosolids were as efficacious as chemical N and phosphorus fertilisers in increasing the growth of nutrient-deficient *Tsuga heterophylla* (Raf.) Sarg. plantations, both in terms of magnitude and duration. Additionally, Ouimet et al. (2015) found that the method of application, whether liquid or dewatered, had no impact on yields. However, growth increases have not been consistently observed. For example, Feldkirchner et al. (2003) reported that paper mill sludge did not result in an increase in wood production. One of the potential risks associated with the use of biosolids as fertilisers is an increase in nitrification. No evidence of this was observed in our study sites.

The low growth response to the single N addition in any form in this study is most likely attributable to the relatively minor alteration in the quantity of N, particularly, the change in N availability induced by the treatments in the humus layer. This indicates that the N availability in the soil was already at a relatively sufficient level prior to the establishment of the experiments, which may have resulted in the observed minimal growth responses. Notwithstanding, the noteworthy correlations between the volume increment and the total N amount, as well as the ammonium-N amount, in the humus layer, particularly in the less fertile pine stands, underscore the pivotal role of N for stand growth. Therefore, it can be concluded that the results of this study are not substantially divergent from those of previous studies, indicating the impact of N availability on growth, albeit not as a result of N addition *per se*. The absence of pronounced effects in our study may also be attributed to the 10-year period that has elapsed since the addition, indicating that the soil has already recovered from the single addition. Consequently, in Sweden, after a period of 10–20 years, several soil properties exhibited no discernible differences any more, even between plots that had been repeatedly N-fertilised and the control plots (Blaško et al., 2013; Högberg et al., 2014 a, b). Conversely, indications on increased N availability has been documented at certain locations over extended periods (Högberg et al., 2014 a,b; Smolander et al., 2022).

The findings of this study corroborate those of previous studies indicating that wood ash alone has typically had a negligible impact on stand growth on mineral soils (Feldkirchner et al., 2003; Saarsalmi et al., 2004, 2014a). In some studies, the addition of ash has been observed to have long-term effects, with a slight acceleration in stand growth over time (Saarsalmi et al., 2014a). Moreover, some studies have indicated that a slight positive growth response to the combined addition of ash and N may occur in the long term, following the response to N alone has ended (Saarsalmi et al., 2012, 2014a). However, the duration of this study was approximately ten years, which is insufficient to uncover potential delayed responses. Further monitoring of the experiments is required to elucidate the long-term effects of ash addition on growth.

The utilisation of wood ash has been put forth as a potential means for mitigating the acidification of forest soils and for offsetting the nutrient losses that arise from the harvesting of trees and the removal of logging residues. The application of wood ash resulted in a discernible decline in soil acidity, a finding that corroborated those of previous studies (Brunner et al., 2004; Saarsalmi et al., 2014a). It is noteworthy that net nitrification was undetectable in all treatments, including those that included combined wood ash and N fertilisation. It can therefore be concluded that the combined fertilisation does not increase the risk of N losses, at least not in the long term. In several studies, the mineralisation of C has been demonstrated to decline as a consequence of N input alone (e.g., Smolander et al., 1995; Janssens et al., 2010). This phenomenon was also observed in in our study sites. The addition of wood ash appeared to counteract this effect, a phenomenon previously observed with wood ash (Saarsalmi et al., 2010, 2012) and also with another soil acidity-decreasing treatment, liming (Smolander et al., 1994).

The findings of this study indicate that stand growth is contingent upon the amount of available N. When N availability is sufficient, the incorporation of additional N in any form does not result in enhanced growth. The single N addition performed 10 years ago had only slight effects on soil properties, indicating a recovery from the addition. Moreover, the utilisation of wood ash and biosolids did not manifest any deleterious consequences at these sites, at least within the medium term. Despite the increase in base cations resulting from ash addition, no enhancement in tree growth was observed. It is important to note, however, that the responses to ash and biosolids addition are dependent on the time elapsed, and that longer-term reactions may differ from those observed in this study.

CRediT authorship contribution statement

Harri Mäkinen: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Antti-Jussi Lindroos:** Writing – review & editing, Investigation, Conceptualization. **Hannu Ilvesniemi:** Writing – review & editing, Investigation, Conceptualization. **Aino Smolander:** Writing – review & editing, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The study was conducted at the Natural Resources Institute Finland (Luke) with the support of grants from the Research Council of Finland (grant numbers 347782 and 348014). We would like to express our gratitude to the staff at the Luke Viikki B2 laboratory for their invaluable assistance with laboratory work and analyses. We would also like to acknowledge the contributions of Ismo Kyngäs and Veijo Salo to the fieldwork.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2024.122467.

Data availability

Data will be made available on request.

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