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Ash fertilization increases long-term timber production in drained nitrogen-poor Scots pine peatlands

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Abstract

Wood ash fertilization remarkably increases tree growth and hence, carbon sequestration in drained boreal peatland forests, particularly in nitrogen (N)-rich Scots pine sites with limited phosphorus (P) and potassium (K). Because ash lacks N, N-deficient ombrotrophic and poor oligotrophic sites are generally considered unsuitable for ash fertilization. In this study, timber production was investigated in six field experiments in N-poor, drained Scots pine dominated peatlands in central Finland, where ash fertilization was applied 15–85 years earlier. Ash significantly increased tree growth in all the study sites. Unfertilized plots showed long-term average mean annual increment (MAI) of 2.01 $m^3 \cdot ha^{-1} \cdot a^{-1}$, whereas in fertilized plots MAI was 4.46 $m^3 \cdot ha^{-1} \cdot a^{-1}$. An analysis with nonlinear mixed effects model revealed a faster volume yield development and higher asymptote of the mean curve in fertilized plots. Higher amount of K in the ash significantly increased the response. Fertilizations were financially lucrative: on average, the break-even cost surpassed the ash fertilization cost (390 € ha^{-1}) more than two-fold at 5% interest rate. The current nutrient status of fertilized trees was rather balanced. The results proved that the long-term growth response to ash fertilization in poor drained peatland sites is comparable to N-rich sites, but the response time is distinctively longer.

Key words: ash fertilization, drainage, peatlands, *Pinus sylvestris*, volume yield, profitability

Introduction

There are only few effective ways to increase carbon (C) sequestration in forests. One is reclamation of previously non-forested areas for timber production by afforestation (Vilén et al. 2016; Menard et al. 2023). Another is to improve the growth of low-productive forests in a permanent manner by, e.g., using genetically improved material in forest regeneration (Serrano-Leon et al. 2021) or using fertilizers to increase the nutrient availability for trees.

Concerning the latter option, nitrogen (N) fertilization has resulted in increased tree stand C sequestration in experimental studies (Shryock et al. 2014; Jörgensen et al. 2021). However, because the response to N fertilization lasts less than 10 years, repeated treatments are needed to enhance long-term tree growth significantly. More permanent improvement in timber productivity can be achieved with fertilization treatment resulting in Type II growth response as defined by Snowdon (2002). Type II or long-term (i.e., 20–35 years) growth responses have been reported in different studies after phosphorus (P) fertilization in P-deficient soils (Pritchett and Comerford 1982; Snowdon 2002; Fox et al. 2006; Trichet et al. 2009). Comparable decades long (30–60 years) responses have also been found in drained N-rich peatland forests after P and potassium (K) or wood ash fertilization (Moilanen et al. 2002; Hökkä et al. 2012). Several studies have shown that stores of mineral nutrients, such as P, K, and boron (B) are low in peat, especially in relation to the N stores (e.g., Kaunisto and Paavilainen 1988; Laiho and Laine 1995; Kaunisto and Moilanen 1998). Peat N content can vary among different sites, mainly depending on site fertility and the peat degree of humification. Because nutrients are released from peat through decomposition, besides peat nutrient content, decomposition rate affects nutrient availability for tree growth (Charman 2002).

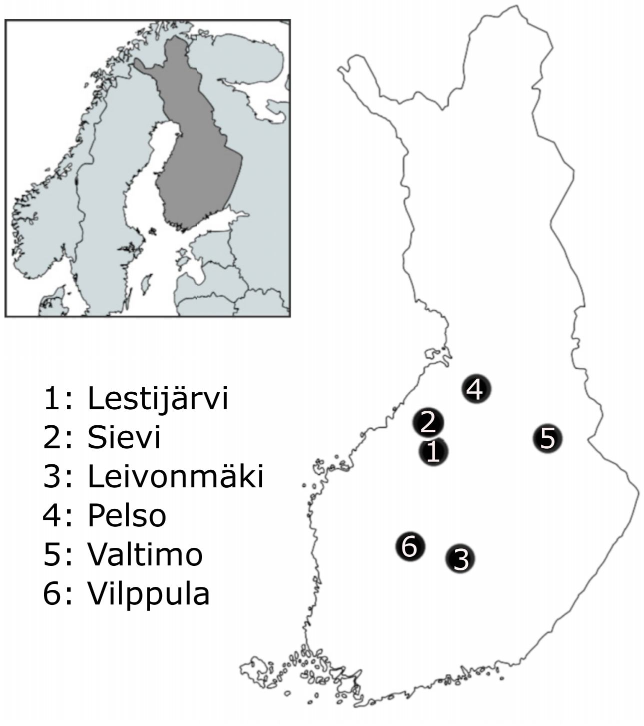
Wood ash is used as a forest fertilizer and it contains all the nutrients that trees need to grow, e.g., P, K, B, and calcium (Ca), except N. In N-rich drained peatland sites, such as type II *Vaccinium-vitis idaea*- and *Vaccinium myrtillus*-sites (classification according to Laine et al. 2012), growth responses to commercial PK fertilizer or wood ash have been shown significant and long-lasting (Moilanen 1993; Hökkä et al. 2012; Moilanen et al. 2015). In these sites the surface peat is commonly well humified and the quantity of N in a 20 cm top peat layer can be 50–100-fold compared to that of K and 30-fold compared to that of P on hectare basis (Kaunisto and Paavilainen 1988; Westman and Laiho 2003). The drawback to the use of fertilization to improve tree growth and consequent C storage in N-rich peatland sites is the increased decomposition rate in peat soil and consequent increased CO_2 production (Moilanen et al. 2012; Ojanen et. al 2019).

In N-poor peatland sites, the surface peat usually consists of poorly humified *Sphagnum* peat, in which the amount of plant available N is low. Many studies have reported that in N-poor drained peatland sites (Dwarf shrub- and *Cladonia*-sites; Laine et al. 2012) PK or NPK fertilization result in only a modest tree growth increase during the first 10–20 years (e.g., Moilanen and Issakainen 1990; Silfverberg and Moilanen 2008). The response of tree growth to N alone is also known to be minor and short-lived (e.g., Hökkä et al. 2012). It has been assumed that in N-poor sites the availability of K in relation to N is more balanced, and thus PK fertilization treatment may not significantly impact stand nutrition and growth (Silfverberg and Moilanen 2008). Based on these results application of PK fertilizers in N-poor drained peatlands has not been recommended.

However, some fertilization studies have proved that in poor drained peatland sites PK fertilization and ash fertilization may also result in significant growth responses. For instance, tentative findings of Veijalainen (2000) showed a growth increase of 1.5–2.0 $m^3 \cdot ha^{-1} \cdot a^{-1}$ over a 20-year period in southern Finland poor pine peatland sites due to PK fertilization. Sikström et al. (2010) reported that adding wood ash (2.5 $t \cdot ha^{-1}$) or PK fertilizer increased pine growth 1.6–1.9 $m^3 \cdot ha^{-1} \cdot a^{-1}$ over 26 years in a poor oligotrophic peatland in southern Sweden. Ernfors et al. (2010) reported a significant basal area growth response of a pine stand to 6.6 $t \cdot ha^{-1}$ dose of wood ash in 5 years on a southern Swedish pine bog. Also, Hytönen and Hökkä (2020) found significant increase in volume growth of a pine sapling stand over a 15-year period following ash fertilization (5 $t \cdot ha^{-1}$) in a poor bog in Central Finland.

These findings suggest that even in N-poor drained sites the peat N availability can be high enough to enable a significant growth response to added PK or wood ash at least in the long-term. Although the growth response appears to be smaller than in N-rich sites, the possibility that poor pine peatlands may also benefit from ash fertilization offers a significant possibility to increase forest C sequestration in these forests, where the soil CO_2 emissions are found to be negligible or negative (i.e., soil is a C sink) even when drained (Minkkinen et al. 2018). Results of Ojanen et al. (2019) also show that application of fertilizer on poor drained peatland site still maintains the soil as a CO_2 sink, which contrasts with the observed change of the N-rich sites to a CO_2 source. In Finland, ash fertilization of drained peatlands has been considered as one of the most important and cost-effective ways to increase the C sinks of land use, land use change, and forestry-sector (Lehtonen et al. 2021). So far, the national fertilization recommendations and forestry policies (e.g., government subsidies for ash fertilization) have directed fertilization efforts to N-rich sites (fertility level *Vaccinium-vitis idaea* or higher). Extending ash fertilization to N-poor drained sites would increase the potential fertilization area by ca. 718 000 ha (Korhonen et al. 2017). To our knowledge, no studies have been conducted on the financial performance of fertilization of drained poor peatlands. The C sequestration achieved via ash fertilization of these low-productive forests can be considered truly additional, which could allow their use as C offset.

Fig. 1. Location of the study sites.



The aim of this study was to investigate the long-term response of drained poor Scots pine peatland sites to ash fertilization in terms of timber production, financial performance, and stand nutrition. The data were based on field experiments followed for several decades after fertilization treatments.

Materials and methods

Study sites and treatments

The study data represented five naturally established and one planted drained peatland Scots pine experimental sites located in Central Finland (Lestijärvi, Sievi, Leivonmäki, Pelso, Valtimo, and Vilppula; Fig. 1, Table 1). Based on the Finnish classification of peatland site types (Laine et al. 2012), all sites were classified as N-poor, i.e., five of them were ombrotrophic and one (Pelso) oligo-ombrotrophic. In all sites the surface peat was poorly decomposed *Sphagnum* peat with low or very low N concentration (Table 1). The peat layer total thickness was more than 1 m in all sites. In five sites the post-fertilization growth periods ranged from 20 to 85 years but in Sievi only 15 years. The study sites were fertilized as young seedling stands or shortly after drainage, when the volume of natural tree stands was low (Table 3). The experiments were established separately at different points of time resulting in dissimilar experimental layouts but if treatments were replicated, they followed randomized design without blocking. The site characteristics are presented in Table 1.

In Valtimo, a pair of two sample plots located on adjacent drainage strips were ash-fertilized every second year (1952, 1954, and 1956) totalling altogether six fertilized plots with

6 t·ha^{-1} dose of wood ash on each (Table 2). Because the original layout did not include a control, two control plots were established and measured in 2001 on an adjacent drainage strip locating next to the 1952 and 1954 ash-fertilized plots. The representativeness of the control plots in terms of similar initial site and stand properties was checked from an aerial photograph taken from the area in 1958.

In Vilppula, the original old natural pine stand was harvested, and the present Scots pine stand originated from seeding in 1916 and the seedling stands were fertilized by wood ash in 1937. Three of the five plots (control, 5 t·ha^{-1}, and 10 t·ha^{-1}) were clear-cut in 1998 and one control and one 5 t·ha^{-1} fertilized plot are still standing.

In Leivonmäki, the tree stand was established by planting 2500 ha^{-1} Scots pine plants after clear-cutting the scattered old natural pine stand and drainage of the site (Paarlahti and Veijalainen 1982).

The amounts of P and K applied in the ashes are shown in Table 2. In Leivonmäki two plots that received N fertilizer alongside with 10 t·ha^{-1} ash treatment were included in the data, as the dose was low (27 kg N ha^{-1}) and N fertilizers have only a modest, short-term effect on tree growth in peatlands (Hökkä et al. 2012). The only information from ashes used in Valtimo and Vilppula is that they originated from burning of wood, and their P and K quantities were estimated based on the applied quantity and concentrations reported from other wood ashes. In Lestijärvi site the ash originated mostly from burning of other fuels than wood, due to which the element concentrations were low and used quantities high (10 and 20 t·ha^{-1}).

Table 1. Characteristics of the study sites.

Site	Coordinates (North, East)	Temperature sum (d.d.)	Altitude (m)	Original site type*	Drainage year	DNM† operations	Ditch spacing (m)	Peat thickness (m)	Peat N concentration (control plots, %)
Sievi	7087702, 374493	1182	114	Low-sedge pine bog with *S. fuscum* hummocs	1974	–	25	1.5	0.59–0.66 (0–20 cm, sampled 2009 ‡)
Pelso	715524, 46614	1008	107	Low-sedge pine bog	1930s	1994–1997	30	>1	1.26 (0–20 cm, sampled 2023)
Lestijärvi	7051146, 386305	1193	148	Dwarf shrub bog	1977	–	40	1.5	1.61 (0–20 cm, sampled 2023)
Leivonmäki	6862122, 444860	1331	131	Ridge-hollow pine bog	1984	–	12	4	0.52 (0–20 cm, sampled 1971§)
Valtimo	7080403, 579181	1198	198	Low-sedge pine bog	1951	2003	45–50, 22–25 after DNM	1.5	0.71 (0–20 cm, sampled 2001)
Vilppula	6882926, 369448	1323	123	Dwarf shrub bog	1909, 1915, 1920	1950s	19, 35	2.2	1.34 (0–10 cm, sampled 1995‖)

[*] According to Laine et al. (2012).
[†] Ditch network maintenance operation.
[‡] Hytönen and Hökkä (2020).
[§] Kaunisto (1972).
[‖] Mikkelä and Takamaa (1995).

Stand measurements

There were altogether 15 control and 31 ash-fertilized plots in the data. In all sites the most recent available stand measurements were conducted between 1993 and 2023 (Table 3). In addition, at least one previous stand measurement was available from all sites so that the total number of tree stand measurements varied from two to five. In the measurements all live stems within the sample plot (size varying from 350 to 1800 m^2 depending on the site) were measured for diameter at breast height (DBH, 1.3 m) by species and mapped. Possible thinning removal has been measured at the time of thinning operation. For sample tree measurements, 15–25 sample trees representing the size distribution of all tally trees were selected and DBH at two directions (mm), tree height (0.1 m), and crown height (0.1 m) were recorded. Sample plot level stand characteristics (e.g., total volume and saw log volume) were calculated using KPL8-program developed in Luke, which utilizes tree-level volume equations of Laasasenaho (1982).

Needle element concentrations

For determining trees' nutrient status, current year needles were collected from the uppermost south-facing whorls of five–seven dominant trees in every sample plot (excluding those three plots in Vilppula, which were clear-cut in 1998) in all sites during dormant period (December–March) during winters 2017–2023. Tree-wise needle samples were

Table 2. Ash doses and phosphorus (P) and potassium (K) amounts ($kg{\cdot}ha^{-1}$) given in the ashes in the study sites.

Site	Year of fertilization	Fertilization treatments	P, $kg{\cdot}ha^{-1}$	K, $kg{\cdot}ha^{-1}$	Number of plots (control/treatment plots)
Sievi	2002	5 $t{\cdot}ha^{-1}$ loose, 5 $t{\cdot}ha^{-1}$ granulated	70	190	2/4
Pelso	1997	5 $t{\cdot}ha^{-1}$ loose, 5 $t{\cdot}ha^{-1}$ granulated	45, 35	140, 100	4/8
Lestijärvi*	1979	10 $t{\cdot}ha^{-1}$ loose, 20 $t{\cdot}ha^{-1}$ loose	16, 32	42, 84	3/6
Leivonmäki	1984	5 $t{\cdot}ha^{-1}$ loose, 10 $t{\cdot}ha^{-1}$ loose	70, 140	180, 320	2/4
Valtimo†	1952–1956	6 $t{\cdot}ha^{-1}$ loose	90	230	2/6
Vilppula†	1937	5 $t{\cdot}ha^{-1}$ loose, 10 $t{\cdot}ha^{-1}$ loose	70, 140	180, 320	2/3

*Very poor-quality mixed ash.
†Estimated on the basis of similar ashes.

Table 3. Timing of the treatments and tree stand measurements in the study sites.

Site	Stand volume at onset ($m^3{\cdot}ha^{-1}$)	Thinning year/mean removal ($m^3{\cdot}ha^{-1}$)	Stand measurements/time elapsed since fertilization
Sievi	1	-/-	2002/0, 2007/5, 2012/10, 2017/15
Pelso	5	-/-	1997/0, 2010/13, 2018/20, 2023/25
Lestijärvi	6–26	-/-	1979/0, 1997/18, 2006/27, 2019/40, 2023/45
Leivonmäki	0	-/-	1984/0, 2008/24, 2020/36
Valtimo	10	Fertilized: 2002/73–122	2002/44–48, 2021/63–67
Vilppula	5–15	Control: 1985/57, 1992/40, 2022/98 Fertilized: 1985/82, 1992/135, 2022/217	1937/0, 1957/20, 1984/47, 1993/56, 2023/85

collected and combined as plot-level samples in the field. Subsequently, the needles were separated in the laboratory, dried at +60 °C, and grinded. C and N concentrations of the needles were analyzed after nitrogen acid (HNO_3) digestion using the Kjeldahl method on a CN analyzer. Concentrations of K, Ca, P, and magnesium (Mg) were analyzed using inductively coupled plasma optical emission spectroscopy. The chemical analyses were carried out at accredited laboratories of the Natural Resources Institute Finland. The concentrations were analyzed against deficiency limits defined in Reinikainen et al. (1998).

Analyzed stand characteristics

We compared the mean annual volume increment MAI ($m^3{\cdot}ha^{-1}{\cdot}a^{-1}$) of the post-fertilization period and total volume yield determined at the last measurement. MAI was calculated for each sample plot by subtracting the initial volume from that at the last measurement and dividing the difference by the number of years elapsed since fertilization. If any thinning treatment was done, the removed volumes were summed to the total yield. Because the initial standing volume at the time of fertilization was not known in Valtimo, it was estimated on the basis of the volume of the unfertilized sample plots measured in 2001 and an aerial photograph taken in 1958.

Total volume yield as a function of time gives an estimate of the timber production potential with and without ash fertilization. Time since fertilization (years) was used as the time variable because no information was available on the stand age at the time of fertilization or at later measurements. Drainage and fertilization operations did not coincide in all sites (e.g., in Vilppula, Sievi, Pelso, and Valtimo), which suggest that there was some variation among stand volumes and stand developmental stage at the time of fertilization. In the nonfertilized plots the timber yield development was driven by the release growth initiated by forest drainage. In fertilized stands, the timber yield was additionally influenced by the ash application.

Statistical analysis

Two-sample *t* test was used to test the effect of fertilization on MAI and volume yield for sites in which the number of replicates was three or more (Lestijärvi, Valtimo, and Pelso). Different ash treatments were not separated, i.e., the treatments were no fertilization = 0 and ash fertilization = 1. The difference was considered statistically significant when $p < 0.05$.

Differences in volume yield between control and fertilized plots in the whole data were analyzed with the following mixed Analysis of variance (ANOVA) model:

$$\text{Yield}_{ij} = \text{Fert} + \text{Time} + \text{Fert} \times \text{Time} + v_j + e_{ij} \quad (1)$$

where Yield_{ij} = volume yield of a sample plot at the last measurement, Fert = fertilization treatment, Time = time elapsed since fertilization, v_j is a random site effect, and e_{ij} is a random residual error. The amount of K in the ash was also tested as an explanatory variable because K was known to be a critical nutrient for the growth of peatland trees (Laurén et al. 2021). The square root transformation was made for volume yield to obtain normally distributed residuals with homogeneous variance. The same model was used for analyzing MAI, but Time and the interaction Fert × Time were excluded, because MAI was already scaled by time. The lmer function in R (R Core Team 2022) was used to estimate the models. Akaike information criterion (AIC), Bayesian information criterion (BIC), and model's loglikelihood value were used in evaluating the goodness of fit of the models.

Because of the nonlinear pattern of volume yield development over time and hierarchical structure of the data with repeated measurements of the same sample plots and several sample plots nested in sites, the analysis of yield development was carried out with the nonlinear mixed effects model utilizing the self-starting logistic growth model as described in Pinhero and Bates (2000, p. 274, 549) and implemented in R nlme package (R Core Team 2022). The form of the logistic growth model is as follows:

$$(2)\qquad Y_{kij} = \frac{\varphi_{1ki}}{1+\exp\left[-\frac{(t_{kj}-\varphi_{2ki})}{\varphi_{3ki}}\right]} + \varepsilon_{kij}$$

where Y_{kij} is the total yield of sample plot i in site k at time point j, t is time since fertilization in site k, and ϕ_1, ϕ_2, and ϕ_3 are model parameters. Parameter ϕ_1 refers to the mean asymptote (Asym) of the total yield, parameter ϕ_2 to the time (xmid) when the total yield reaches half of the Asym, and parameter ϕ_3 (scale) refers to time elapsed between reaching half of the Asym and approximately $\frac{3}{4}$ of the Asym (Pinhero and Bates 2000, p. 549). Term ε_{kij} is the residual error.

The parameters ϕ_i of the logistic model with random effects can be expressed as follows (Pinhero and Bates 2000):

$$(3)\qquad \varphi_i = \beta + \boldsymbol{b}_{ki} + \boldsymbol{c}_k$$

where $\boldsymbol{\beta}$ is the population average value of parameter ϕ_i, $\boldsymbol{b}_{kj}$ represents random deviation of ϕ_i from the average at sample plot i in site k, and $\boldsymbol{c}_k$ represents deviation of ϕ_i from the average at site k. The random effects were assumed to be independent for different sample plots and sites, and the errors ε_{ijk} were assumed to be independent of the random effects (Pinhero and Bates 2000). The model's fixed parameters and standard deviations of the random effects were estimated with the R nlme package. AIC, BIC, and loglikelihood were used as the model evaluation criteria.

The differences in the measured nutrient concentrations and N% of the needles between fertilization treatments and nonfertilized controls were tested both site-wise and over the whole data by using nonparametric Mann–Whitney U-test.

Financial performance

To estimate the profitability of the fertilization, the break-even analysis (see, e.g., Chu et al. 2022) was applied. In the break-even analysis the maximum fertilization cost was calculated to correspond to the increased present value of timber revenues due to growth response to fertilization. Technically, we constructed a spreadsheet application in which the growth response (due to fertilization) associated with each sample plot could be fed, as well as the proportion of sawlogs based on the observed measurements. Then, a series of 5-year intervals after the fertilization was set to cover a timeline between 5 and 40 years after fertilization. Finally, for each 5-year time interval the break-even cost of fertilization was calculated by iterating with a spreadsheet optimization application (Microsoft 365 Apps for enterprise). A relatively long time span after the fertilization (up to 40 years) was applied to secure that the break-even cost reaches its optimum with certainty. Sievi site was excluded from the analysis because the tree stand was of noncommercial size at the time of last measurement (15 years after fertilization).

Table 4. Stumpage prices in real terms by felling method (first thinning, thinning, and regeneration felling), € m^{-3}.

Timber assortment	First thinning	Thinning	Regeneration felling
Scots pine, sawlogs	41.87	51.22	60.49
Scots pine, puplwood	12.92	16.38	19.41
Norway spruce, sawlogs	43.32	52.10	61.87
Norway spruce, pulpwood	12.74	16.83	20.78
Birch*, sawlogs	34.95	39.52	46.53
Birch, pulpwood	12.63	15.76	18.80

*All deciduous tree species.

Formally, the maximum fertilization cost, $\text{MAXF}_{\text{COST}}$ to break even with increased present value of timber revenues was solved according to

$$(4)\qquad \text{MAXF}_{\text{cost}} = \frac{\Delta TR_t}{(1+r)^t}$$

where $\text{MAXF}_{\text{COST}}$ is the break-even fertilization cost (i.e., the maximum fertilization cost to break even), € ha^{-1}, ΔTR_t is increased timber revenues (compared to control without fertilization) at time t, r is interest rate (here 5%), and t {5,40}. Note that with increasing t (5→40) $\text{MAXF}_{\text{COST}}$ corresponds to a function with a single maximum and a decreasing slope toward the endpoint.

The stumpage prices used were based on the time series of 10-year period covering years 2012–2021 (https://statdb.luke.fi/PxWeb/pxweb/en/LUKE/). We consider the 10-year time span long enough to capture the peaks and bottoms of economic cycles in Finland. The nominal values were converted to real prices through deflation (applying the cost-of-living index of Statistics Finland 2021; https://stat.fi/en/statistics/khi#tables) after which arithmetic averages were calculated. The average stumpage prices are presented in Table 4.

Results

MAI

The stand level MAI of fertilized plots varied from 0.60 to 7.89 $m^3 \cdot ha^{-1} \cdot a^{-1}$, with an average of 4.46 $m^3 \cdot ha^{-1} \cdot a^{-1}$

Fig. 2. Mean annual increment, MAI ($m^3 \cdot ha^{-1} \cdot a^{-1}$ ± SEM (standard error of mean)) and total volume yield ($m^3 \cdot ha^{-1}$ ± SEM) in control and ash-fertilized plots. The average length of time period applied for calculating MAI and total volume yield was 41 years for control and fertilized plots.

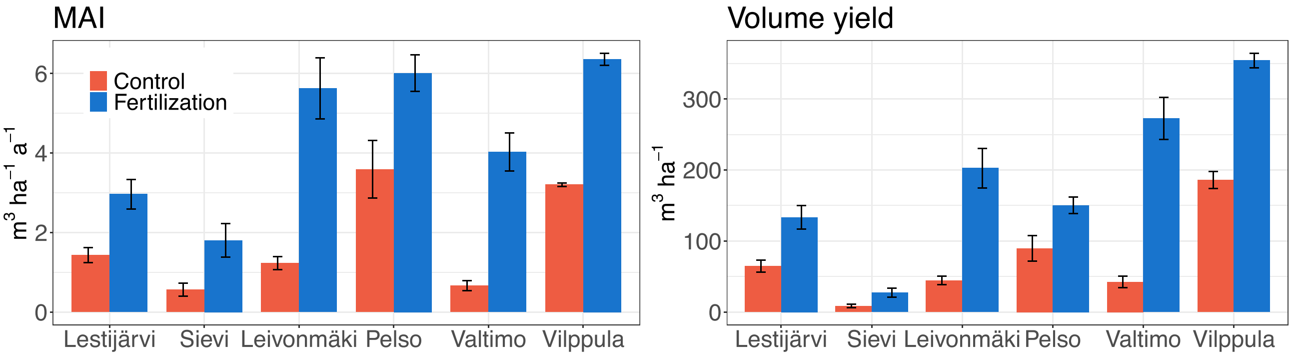


Table 5. Results of a mixed Analysis of variance model (eq. 1) for mean annual increment (MAI) and square root of total volume yield defined at the last measurement of the data.

	MAI			Volume yield		
Variable	Estimate	s.e.	*t*-value	Estimate	s.e.	*t*-value
Intercept	1.770	0.651	**2.721**	4.088	2.016	**2.027**
Fert*	0.764	0.653	1.169	− 1.288	1.359	− 0.948
Time				0.103	0.040	**2.607**
K$^{\dagger)}$	0.011	0.003	**3.110**	0.020	0.006	**3.407**
Fert × Time				0.071	0.026	**2.728**
s.d.(v_j)	1.453			2.507		
s.d. (e_{ji})	1.004			1.567		
AIC	158.2			203.8		
BIC	167.3			216.6		
LogLike	−74.1			−94.9		

Note: Statistically significant values are shown in bold. s.e., standard errors; s.d., standard deviations; AIC, Akaike information criterion; BIC, Bayesian information criterion; LogLike, model's loglikelihood.
*A group indicator variable, fertilization treatment = 1, control = 0.
†= the amount of potassium in the given ash dose, $kg \cdot ha^{-1}$.

during the period from establishment to the last measurement (41 years on average) (Fig. 2). In control plots the MAI varied from 0.39 to 4.21 $m^3 \cdot ha^{-1} \cdot a^{-1}$, and the average was 2.01 $m^3 \cdot ha^{-1} \cdot a^{-1}$ (41 years on average). On average, the increase in MAI due to the ash fertilization during the study period was thus 2.45 $m^3 \cdot ha^{-1} \cdot a^{-1}$.

According to site-specific *t* test, statistically significant differences between control and fertilized plots in MAI were found in Lestijärvi ($p = 0.009$), Pelso ($p = 0.049$), and Valtimo ($p = 0.001$).

In the combined data, only the treatment variable Fert was statistically significant in the mixed ANOVA model explaining differences in MAI between the control and fertilized plots. If the amount of K in the ash dose was used as a predictor, the effect of Fert became nonsignificant (Table 5).

Volume yield

The mean volume yields were 194.0 and 89.4 $m^3 \cdot ha^{-1}$, for fertilized and control plots, respectively (Fig. 2). According to site-specific *t* tests, the differences in volume yield squared between control and fertilized plots were significant in Lestijärvi ($p = 0.021$) and Valtimo ($p = 0.000$), and close to significant ($p = 0.080$) in Pelso.

In the combined data, the time since fertilization, the interaction between time and fertilization treatment, and the amount of K were statistically significant variables in the mixed ANOVA model explaining differences in volume yield between control and fertilized plots (Table 5).

Modelling volume yield development

Equation 2 was fit to fertilized and nonfertilized plots separately because their development was very different especially in terms of the mean Asym. A preliminary analysis with nls package (R Core Team 2022) was done to find approximate starting values for the nonlinear parameters for both fertilized and control plots. The oldest post-fertilization measurements, obtained at 85 years after fertilization from one control plot and one 5 $t \cdot ha^{-1}$ fertilization plot in Vilppula site were omitted, because as single points they were considered outliers compared to most of the data and possibly could have a significant impact on the results.

Table 6. Parameter estimates and their standard errors (s.e.) and standard deviations (s.d.) of the total volume yield models (eq. 2) for fertilized and control plots.

Fertilized plots ($n = 31$)			Control plots ($n = 15$)		
Fixed part	Estimate	s.e.	Fixed part	Estimate	s.e.
Asym	333.78	31.93	Asym	131.6	41.46
xmid	35.67	1.69	xmid	33.18	4.70
scale	12.76	0.76	scale	12.86	2.78
Random part	Estimate	ci*	Random part	Estimate	ci*
sd(Asym_i/site)	0.006	n.a. †	sd(Asym_i)	85.11	43.15–167.87
sd(Asym_{ij}/plot)	141.16	n.a.			
sd(e_{kij})	2.75	n.a.	sd(e_{kij})	16.41	13.05–20.65
AIC	842.32			402.37	
BIC	857.18			411.29	
LogLike	– 414.16			– 196.19	

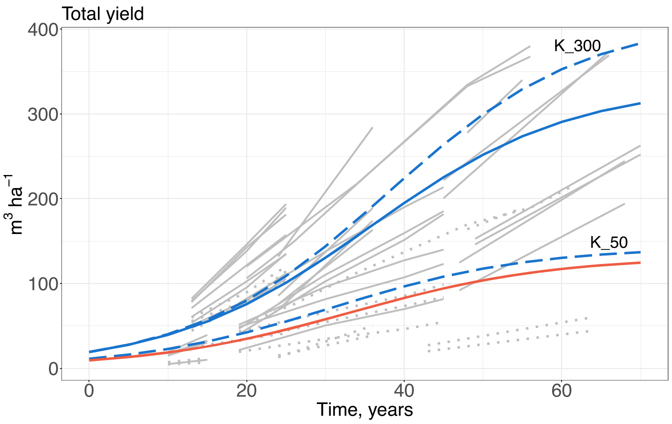
Note: AIC, Akaike information criterion; BIC, Bayesian information criterion.
*95% confidence interval.
†Not available.

To account for the increasing variance of volume yield over time, a linear variance function with respect to time was included in the model for fertilized plots. A model assuming all parameters ϕ_i to vary among sites and sample plots showed that the standard deviations of xmid and the scale were much smaller than that of Asym and, based on their estimated confidence intervals, did not deviate from zero. This suggested that only the Asym included significant random variation, which was clearly higher among the sample plots within the sites than that among the sites. A model with mean fixed parameters (Asym, xmid, and scale) and random effect associated with the Asym was found sufficient to describe the mean development of the total volume yield as a function of time for the fertilized stands (Table 6). The fixed part indicated that the mean Asym of total yield was 334 m^3·ha^{-1} and half of that (i.e., ϕ_2, 167 m^3·ha^{-1}) was achieved in 36 years after fertilization.

Similar procedure was carried out for control plots. Especially the value of Asym of the fixed parameters greatly deviated from that of the fertilized stands (Table 6). Significant random variation in Asym was observed at site level, while the other parameters xmid and scale did not show significant random variation. For control plots, the variance function was nonsignificant. The Asym for controls total yield was 132 m^3·ha^{-1}, and half of that (66 m^3·ha^{-1}) was achieved at 33-year time point.

Despite the large variation, the volume yield development showed continuously increasing trend throughout the observation period and there was a continuously increasing difference between the average yield curves of control and fertilized plots (Fig. 3).

Fig. 3. The average volume yield development as a function of time since fertilization for control (red solid line) and fertilized (blue solid line) plots predicted according to models in Table 6. Straight lines in grey represent measured total volumes for the ash-fertilized (solid lines) and for the control (dotted lines) plots. Volume yield development predicted by the model is shown in Table 7, when amounts of potassium (K) in the used ash are low (50 kg·ha^{-1}, lower blue broken line) or high (300 kg·ha^{-1}, higher blue broken line).



The effect of fertilization treatment on the volume yield curve was further investigated by including additional variables in the model. Based on the result from the mixed ANOVA model (Table 5), we expressed Asym and xmid as a function of the quantity of K (kg·ha^{-1}) in the ash, transformed as K/(K + 30) (Table 7). According to the AIC, BIC, and loglikelihood, the resulting model showed better fit to the data than the mean model (Tables 6 and 7). The ANOVA test also suggested that the model with K affecting the Asym and xmid was better ($p < 0.000$). However, total random variation related to Asym was higher than that in the mean model.

When the model was applied with low (50 kg·ha^{-1}) and high (300 kg·ha^{-1}) amounts of added K, the resulting yield development curves were located below and above the mean curve and covered a large part of the variation of the measured yields (Fig. 3). There were, however, some plots that developed faster than the prediction of the high K dose. With the low K dose, the curve was only slightly higher than that of the mean curve of the control plots.

Table 7. Parameter estimates and their standard errors (s.e.) and standard deviations (s.d.) of a total volume yield model (eq. 2) for fertilized plots when the amount of potassium (K) is used as an explanatory variable.

Fixed part	Estimate	s.e.
Asym	– 450.55	280.88
Asym.K_m*	949.42	337.58
xmid	15.37	10.58
xmid.K_m	24.70	12.30
scal	12.51	0.73
Random part		
s.d.(Asym_i/site)	121.75	
s.d.(Asym_{ij}/plot)	77.16	
s.d.(e_{kij})	2.60	
AIC	820.28	
BIC	840.10	
LogLike	– 402.14	

Note: AIC, Akaike information criterion; BIC, Bayesian information criterion.
*K_m = K/(K + 30).

Foliar element concentrations

Despite the long time that has passed since fertilization, the nutrient status of trees growing in fertilized plots was relatively good (Figs. 4*a* and 4*b*). While the differences between the control and fertilization treatments did not show statistical significance within the experiments, significant effects of fertilization treatments on needle K and P were evident across the entire dataset (Fig. 4*a*). Of the fertilized sample plots, the needle K concentrations were below the deficiency limit (<3.5 mg·g^{-1}; Reinikainen et al. 1998) in one site (Leivonmäki; Fig. 4*b*). Needle P content was below the deficiency limit (1.3 mg·g^{-1}) in fertilized plots in two sites (Lestijärvi and Sievi). Control plots showed deficiency of some of the main nutrients in all sites. In Sievi, Pelso, and Lestijärvi the control plots showed lack of both N and P, while in the southernmost sites Vilppula and Leivonmäki N was abundantly available.

Financial performance

The range of break-even fertilization costs fluctuated between ca. 74 € ha^{-1} and 1946 €/ha with 5% interest rate, depending on the treatment, location, and timing, i.e., when increased growth was assumed to be realized (Fig. 5). The best financial performer was in Valtimo with treatment “6T_56” resulting in a range from 1011 € ha^{-1} to 1946 € ha^{-1} (Fig. 5). The lower value (1011 € ha^{-1}) corresponding to a situation where increased growth (due to fertilization) is realized 5 years after fertilization, which is too soon as anticipated. The higher value, 1946 € ha^{-1} corresponds to a significant growth response within 20 years since fertilization. On the other hand, in Lestijärvi the highest break-even fertilization cost was only 514 € ha^{-1}, which is considered a low value, given that a 10-year average fertilization cost (deflated) in Finland is ca. 388 € ha^{-1} (see https://statdb.luke.fi/PxWeb/pxweb/en/LUKE/). In Lestijärvi treatment “10T” and in Pelso treatment “5T_G” the break-even cost was below the current ash fertilization cost. The average of the highest break-even fertilization cost in each location was 902 € ha^{-1}, which is more than a double of the current average fertilization cost, 388 € ha^{-1}.

Discussion

The results showed that in N-poor Scots pine peatlands fertilization with wood ash increases average MAI and volume yield to more than two-fold when compared to the nonfertilized control plots in the long-term (approximately 40 years). This is a new result, contradicting the previous understanding that insufficient availability of N in nutrient-poor peatland sites is limiting the response of trees to ash fertilization. Our findings indicate a distinct growth response to ash in all sites of our data.

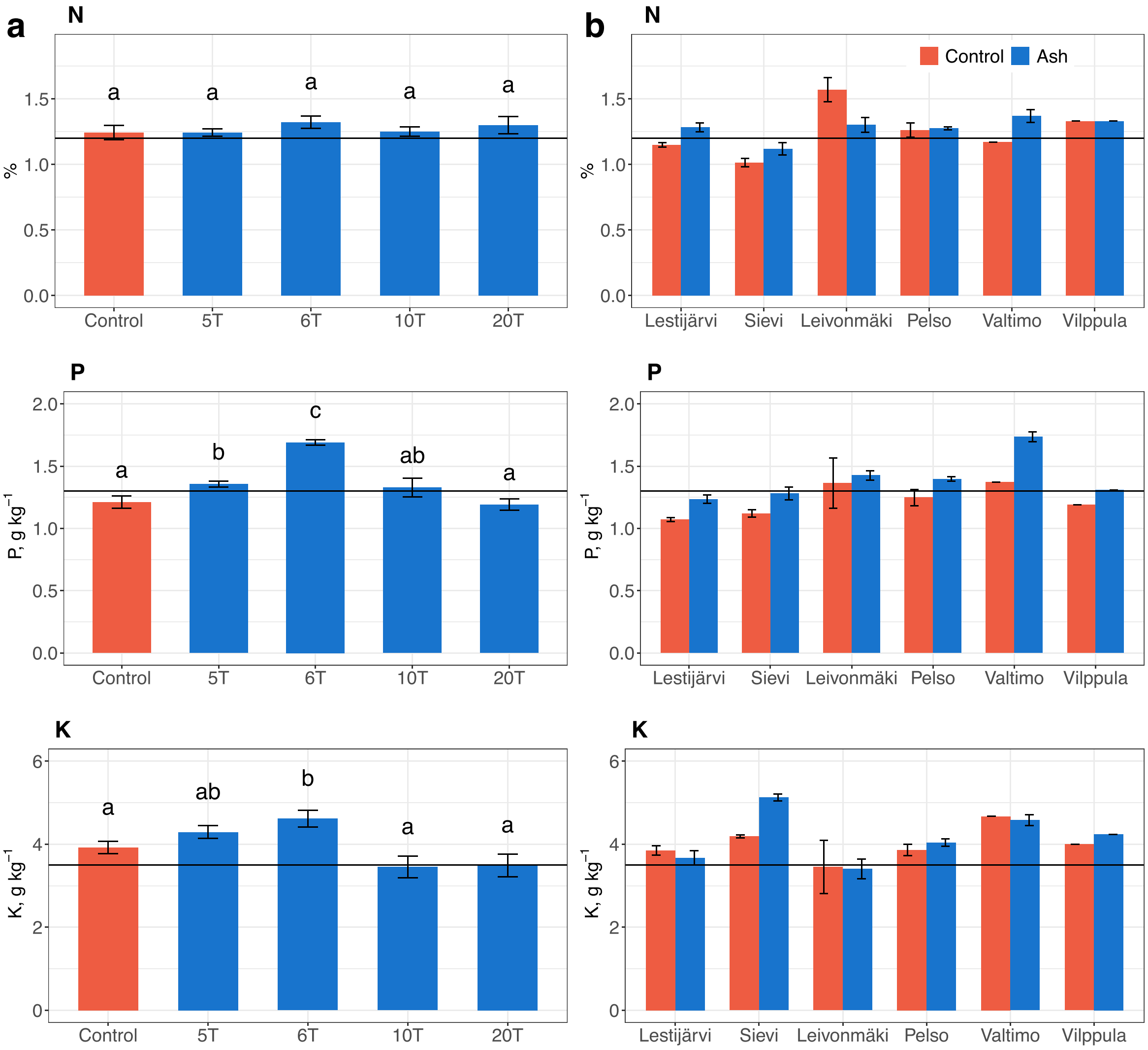
Some sites (Sievi, Valtimo, and Leivonmäki) represent so poor peatlands that drainage merely cannot increase their growth sufficiently to lift them to forest land category, i.e., according to Finnish definition, their average MAI in 100 years rotation remains below 1 m^3·ha^{-1}·a^{-1}. In Vilppula, Pelso, and Lestijärvi, however, also the nonfertilized stands were forest land (MAI varied between 1.2 and 4.6 m^3·ha^{-1}·a^{-1}). Nevertheless, ash fertilization appeared to increase timber productivity of such poor sites significantly.

Testing the differences in MAI and volume yield between control and fertilized plots in each site separately indicated significant differences in three of the six sites. In the combined data the effect of ash treatment became clearer and the mixed ANOVA models showed that both MAI and total yield were significantly higher in ash-fertilized plots that in the control plots. Also, the amount of K in the ash had a significant impact on both.

In N-rich pine peatlands, the average long-term growth response to ash application has varied between 1.0 and 3.0 m^3·ha^{-1}·a^{-1} for 35–40 years (Hökkä et al. 2012; Moilanen et al. 2015). Much higher responses (up to 6.5 m^3·ha^{-1}·a^{-1}; Moilanen et al. 2002), depending on the ash dose and peat properties, have been reported also. However, a clear difference can be observed between N-rich and N-poor sites in the rate of the response. Applying ash or PK on N-rich peat soils, the maximum growth response was achieved in 10–15 years (Moilanen 1993; Hökkä et al. 2012; Moilanen et al. 2012). The nonlinear mixed effect model (Table 6) showed that in these data the average annual volume yield developed at a much slower rate, i.e., at 20 years since fertilization the additional average volume yield was 1.5 m^3·ha^{-1}·a^{-1}, assuming equal initial volumes. However, the average increase in MAI at 40-year time point was 2.5 m^3·ha^{-1}·a^{-1}. This is comparable to the mean growth response previously found in N-rich sites but achieved within a much longer time. Longer response time of poor oligotrophic sites was also found by Hökkä et al. (2012).

The more specific model of Table 7 showed that the amount of K in the ash explained the Asym and xmid, and as a result, both the Asym and the form of the curve were different if different doses of K were applied, thus making it possible to capture a large part of the variability of the responses among plots and sites (Fig. 3). Still, there was significant residual variation not explained by the model. We

Fig. 4. (*a*, *b*) Mean foliar nitrogen (N), phosphorus (P), and potassium (K) concentrations and ± SEM (standard error of mean) by fertilization treatments in the whole data (*a*). Statistically significant differences (Mann–Whitney U-test) are indicated by different letters above the columns. Mean foliar nutrient concentrations and ± SEM by study sites and treatments (control and ash) (*b*). Deficiency limits (Reinikainen et al. 1998) are indicated by a horizontal line. For ash, the concentrations are means of different ash treatments.



know that ditching intensity has only a marginal impact on stand growth when compared to, e.g., the effect of fertilization (Ahtikoski and Hökkä 2019). Also, the sites were considered rather homogeneous in terms of timber productivity, all belonging into scrub land or low-productive forest land category even when drained. No trend was found in model residuals with respect to these site quality classes. As all the sites were located within a narrow climatic range, the geographical location (temperature sum) did not explain the response.

The used ashes varied in terms of their nutrient contents from very poor to very rich. Moilanen et al. (2005) expressed the growth response of Scots pine stands to ash fertilization on N-rich drained peatlands in relation to the given amount of P, but as shown in their results, P and K were almost equally correlated with growth. In our data the volume yield correlated slightly higher with K (0.34) than for P (0.33). According to the previous studies, K is the most growth limiting nutrient in drained peatlands (Laurén et al. 2021). After PK fertilization, a relatively low amount of P (40–45 kg·ha^{-1}) is sufficient to sustain sufficient foliage P concentrations for decades, while K concentrations tend to decrease after 20 years (Silfverberg and Moilanen 2008). That was also shown in our data, where the foliar P concentration was still satisfactory with the lowest given dose (16–50 kg·ha^{-1}) (Fig. 6). As a water-soluble nutrient, K may leach from the ash easier than P (e.g., Callesen et al. 2017) and become limiting again. Thus, we assumed that beyond this minimum amount of P given in fertilizer, the quantity of K in the ash becomes important and affects the magnitude of the response. Figure 3 showed that with poor ash, i.e., ash with low K concentration, the volume development was not much better than that of the

Fig. 5. The break-even fertilization cost associated with each location, treatment, and timing, € ha^{-1}. The bottom of a bar represents break-even fertilization cost when increased growth is realized 5 years after fertilization and the top of a bar illustrates the highest break-even fertilization cost achievable within the timeline of *t* {5,40}. Other break-even values fall between the two extremes. The point in each column represents the average break-even cost (€/ha) when *t* {5,40}, and the horizontal line current fertilization cost (388 € ha^{-1}). Interest rate 5%. The fertilizer treatments are 5T, 10T, and 20T = 5, 10, and 20 t·ha^{-1} of loose ash, 5T_L, 5T_G = 5 t·ha^{-1} loose or granulated ash, 6T_52–6T_56 = 6 t·ha^{-1} loose ash applied between 1952 and 1956.

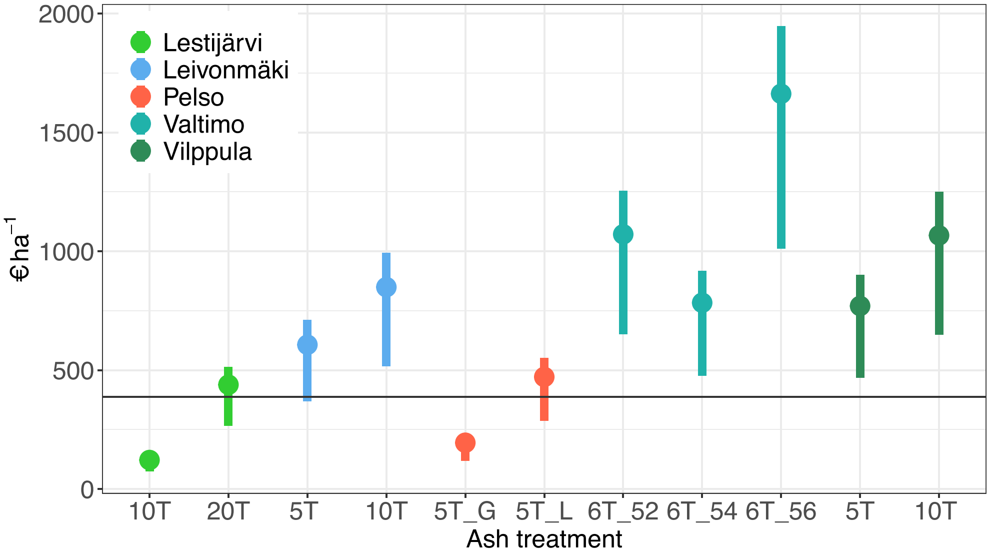
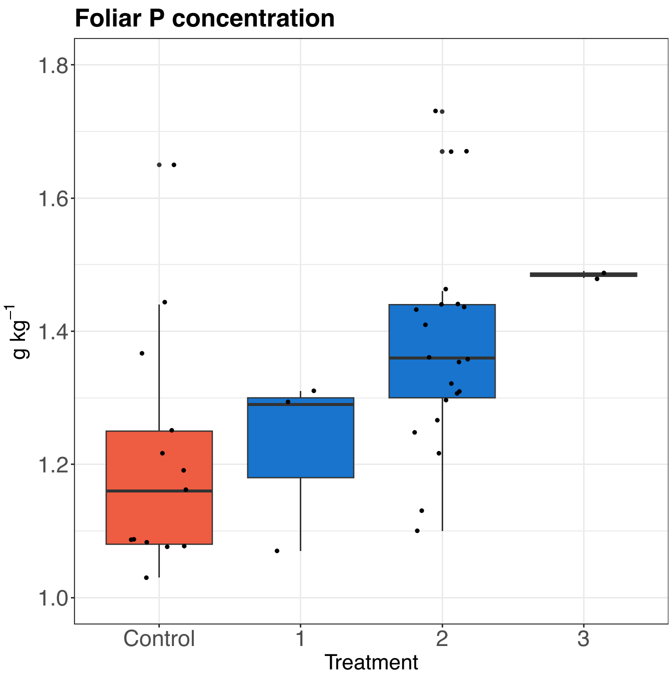


Fig. 6. Box-plot of the foliar phosphorus (P) concentration with different amounts of P in the ash (Treatments: 0 = control, 1 = 16–45 kg·ha^{-1}, 2 = 70–90 kg·ha^{-1}, and 3 = 140 kg·ha^{-1}).



nonfertilized control plots. Accordingly, high ash dose did not compensate for poor quality (low nutrient content; Fig. 4).

Granulated ash was used in Sievi and in Pelso, while in the other experiments loose wood ash was used. Currently, granulated ash is almost entirely available for ash fertilization. Based on results of Hytönen and Hökkä (2020), the form of ash will influence the growth response time: with loose ash the response is several years quicker. Except the Lestijärvi site, the nutrient amounts applied in these data were also rather high. Because of these reasons, responses slower (and lower financial outcome) than those found in this study can be expected in practice if granulated ash is applied. It is, however, possible that the time ash promotes growth will be longer because nutrients will be released at slower pace from granulated ash (Callesen et al. 2017; Hytönen and Hökkä 2020).

In general, the foliar nutrient concentrations of the fertilized plots were at a satisfactory level, considering the long time elapsed since fertilization and on average, the concentrations of K and P were mostly higher in the fertilized stands than in the nonfertilized controls. Despite the fact that significant differences still appeared in the concentrations of P, the effect of fertilization on the trees' nutrient status has mostly vanished. Based on the very low K and P concentrations in needles, there was a need of re-fertilization in Lestijärvi and Leivonmäki sites (Fig. 4*b*). In Lestijärvi the low foliar concentrations can be explained by the use of low-quality mixed ash in which the given quantities of K and P remained clearly below the current recommendations for ash fertilization (Table 2). Although these were nutrient-poor sites, the availability of N on control plots was good in Vilppula and very good in Leivonmäki (c.f. Moilanen et al. 2010).

The financial performance related to ash fertilization demonstrated to be promising: the average of the highest break-even fertilization cost among the study locations was 902 € ha^{-1} (interest rate 5%), which is more than a double of the current average fertilization cost, 388 € ha^{-1}. In other words, ash fertilization tends to be financially lucrative. This result coheres with earlier studies (Rantala and Moilanen 1993; Moilanen et al. 2015) on the profitability of fertilization on peatland forests. A recent study (Ahtikoski and Hökkä 2019) showed that fertilization was more important single factor for overall profitability than ditch network maintenance (DNM) on peatland forests. Further, the relative importance of fertilization (compared to DNM) increased toward North (Ahtikoski and Hökkä 2019).

The data are exceptional because the study period was distinctively long, up to 60–85 years of monitoring after ash application. The clearly shorter follow-up periods (5–15 years) in Moilanen and Issakainen (1990) and Moilanen (1993) studies may be the main reason for the previous conclusion that the growth response to fertilization was modest in N-poor sites. The data of this study did not show the stand development over the whole rotation either. There were only few observations from stands approaching maturity, which in fact may have affected the estimate of Asym. Only in Vilppula and Valtimo, the fertilized plots were mature in terms of basal area weighted mean DBH (23.0–28.8 cm) based on forest management recommendations (Äijälä et al. 2019). The other stands were thinning stands (mean diameter 13.0–18.2 cm) and could be grown for 10–30 years more before maturity. Of the nonfertilized controls, only Vilppula control plot was mature (mean diameter 26.0 cm). In other control plots it is unlikely that the mean diameter limit for regeneration maturity will be reached. It is thus expected that the difference in mean MAI and volume and saw log yields will increase further until all the fertilized plots have reached maturity.

This study was not able to explain all the factors behind the rather good, long-lasting growth responses to ash drained of N-poor pine peatlands. The quality of ash, i.e., K amount appeared to be one important factor. It is likely that improved N availability, induced by the long-term increase in peat decomposition rate also plays a significant role. Firstly, drainage itself increases peat decomposition, as the water level drawdown decreases anoxia in the soil. All the studied sites have been drained for forestry for a long time, ranging from 46 years (Lestijärvi) to 113 years (Vilppula). Additionally, the subsidence and compaction of the peat layer bring the nutrient stores of deeper peat layers accessible to the trees, both making poor drained sites generally more suitable for tree growth. Moilanen et al. (2010) pointed out that N deficiency, when defined from foliar nutrient samples, is becoming less common also in N-poor drained peatlands. Laiho and Laine (1995) observed an increase in peat N and P stores of N-poor sites with increasing time since drainage. Since peat decomposition rate is highly depended on temperature, the warmer and longer growing seasons may accelerate it even further (Updegraff et al. 2001). Moilanen et al. (2010) found that in peatland Scots pine stands higher foliar N concentrations were related to higher temperature sum. Decomposition processes, driven by microbial activity in the soil, are also enhanced by the added Ca, which increases soil pH (Moilanen et al. 2002; Peltoniemi et al. 2016), which in turn release more N for vegetation. Concurrently, the foliar N was higher in ash-fertilized plots in three study sites (Pelso, Lestijärvi, and Valtimo), indicating increased N availability. On the other hand, some studies have shown that also commercial PK fertilizers have clearly enhanced tree growth in poor peatlands (Veijalainen 2000; Sikström et al. 2010). This result was supported by the Lestijärvi site of this study, where PK fertilization has significantly improved stand growth (data not shown) suggesting that addition of Ca may not be a crucial requirement for enhanced growth.

The data were not enough for building representative yield equations, but sufficient to visualize and quantify the average change in long-term timber productivity resulting from ash fertilization through the nonlinear mixed effect modelling. Our results showed that ash fertilization clearly increases timber production in N-poor drained peatlands, that with a higher amount of K in the ash, a quicker and greater response can be achieved, and that the increase in timber production is comparable to that observed in N-rich peatland sites but takes place at a much slower rate. Nevertheless, the growth response was sufficient to make these fertilization investments financially feasible in most of the studied sites.

The observed growth response may offer a valuable tool for additional C sequestration from the atmosphere into the growing tree stock and therefore aiding climate mitigation efforts. Since fertilization increases tree growth, and thus C storage in living trees, it also creates an opportunity to gain revenues by sequestering C in forests. If there was a price mechanism for private forest owners to receive payment for sequestered C, this would increase forestry revenues as well (see Assmuth et al. 2018; Fig. 5) Currently, such a mechanism for private forest owners does not exist in Europe (cf. The European Union Emissions Trading System, EU ETS "gap and trade" system that excludes private forest owners).

However, in considering whether ash fertilization has potential for climate change mitigation, the net effect of ash fertilization on ecosystem C balance needs to be accounted for. Further, the C balance must be compared against a reference system, i.e., unfertilized, drained peatland forests. In drained peatland forests the net CO_2 emissions from the soil due to loss of peat are often significant. Previous research has shown that even after drainage, most peatland forests continue to act as C sinks because of the enhanced tree growth (Ojanen et al. 2013). In N-poor sites, tree growth is slow, but the forests remain a C sink due to low or negligible CO_2-emissions from the soil (Minkkinen et al. 2018). Conversely, in N-rich sites, the C sink is driven by high level of tree growth, outweighing substantial soil CO_2 emissions. The concern is whether ash fertilization changes the ecosystem function in such a way that the N-poor sites, similarly to N-rich sites, become a net source of CO_2 from the soil. Consequently, although ash fertilization shows significant promising prospects for climate change mitigation, a degree of uncertainty remains regarding its potential long-term effects on the soil processes.

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Data availability

Data generated or analyzed during this study are available from the corresponding author upon reasonable request.

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Competing interests

The authors declare there are no competing interests.

References

Ahtikoski, A., and Hökkä, H. 2019. Intensive forest management—does it financially pay off on drained peatlands? Can. J. For. Res. **49**: 1101–1111. doi:10.-1139/cjfr-2019-0007.

Äijälä, O., Koistinen, A., Sved, J., Vanhatalo, K., and Väisänen, P. (*Editors*). 2019. Metsänhoidon suositukset. [Recommendations for forest management] Tapion julkaisuja. ISBN 978-952-5632-75-0. 255p. [In Finnish].

Assmuth, A., Rämö, J., and Tahvonen, O. 2018. Economics of size-structured forestry with carbon storage. Can. J. For. Res. **48**(1): 11–22. doi:10.1139/cjfr-2017-0261.

Callesen, I., Ingerslev, M., and Raulund-Rasmussen, K. 2017. Dissolution of granulated wood ash examined by in situ incubation: effect of tree species and soil type. Biomass Bioenergy, **31**(10): 693–699. doi:10.1016/j.biombioe.2007.06.014.

Charman, D. 2002. Peatlands and environmental change. John Wiley and Sons Ltd.

Chu, L., Grafton, R.G., and Nguyen, H. 2022. A global analysis of the break-even prices to reduce carbon dioxide via plantation and avoided deforestation. For. Policy Econ. **135**(2022): 102666. doi:10.1016/j.forpol.2021.102666.

Ernfors, M., Sikström, U., Nilsson, M., and Klemedtsson, L. 2010. Effects of wood ash fertilization on forest floor greenhouse gas emissions and tree growth in nutrient poor drained peatland forests. Sci. Total Environ. **408**(20): 4580–4590. doi:10.1016/j.scitotenv.2010.06.024.

Fox, T.R., Allen, L.H., Albaugh, T.J., Rubilar, R., and Carlson, C.A. 2006. Forest fertilization in southern pine plantations. Better Crops, **90**(3): 12–15.

Hökkä, H., Repola, J., and Moilanen, M. 2012. Modelling volume growth response of young Scots pine (*Pinus sylvestris*) stands to N, P, and K fertilization in drained peatland sites in Finland. Can. J. For. Res. **42**(7): 1359–1370. doi:10.1139/X2012-086.

Hytönen, J., and Hökkä, H. 2020. Comparison of granulated and loose ash in fertilisation of Scots pine on peatland. Silva Fenn. **54**(2): 10259. doi:10.14214/sf.10259.

Jörgensen, K., Granath, G., Lindahl, B.D., and Strengbom, J. 2021. Forest management to increase carbon sequestration in boreal Pinus sylvestris forests. Plant Soil, **466**: 165–178. doi:10.1007/s11104-021-05038-0.

Kaunisto, S. 1972. Effect of fertilization on successful planting and the number of naturally born seedlings on a fuscum bog at Kivisuo experimental field. Folia For. **139**. 1–10. [In Finnish with English summary].

Kaunisto, S., and Moilanen, M. 1998. Kasvualustan, puuston ja harvennuspoistuman sisältämät ravinnemäärät neljällä vanha ojitusalueella. [Amounts of nutrients contained by the soil, the standing trees, and the thinning removal in four old drainage areas]. Metsätieteen Aikakauskirja, **3**: 393–410. [In Finnish].

Kaunisto, S., and Paavilainen, E. 1988. Nutrient stores in old drainage areas and growth of stands. Commun. Inst. For. Fenn. **145**: 1–39.

Korhonen, K.T., Ihalainen, A., Ahola, A., Heikkinen, J., Henttonen, H.M., Hotanen, J-P., et al. 2017. Suomen metsät 2009–2013 ja niiden kehitys 1921–2013. [Finnish forests 2009–2013 and their development from 1921 to 2013]. Luonnonvara-ja biotalouden tutkimus 59/2017. Luonnonvarakeskus, Helsinki. 86p. [In Finnish].

Laasasenaho, J. 1982. Taper curve and volume functions for pine, spruce and birch. Communicates Instituti Forestalis Fenniae, **108**. 74p.

Laiho, R., and Laine, J. 1995. Changes in mineral element concentrations in peat soils drained for forestry in Finland. Scand. J. For. Res. **10**(3): 218–224. doi:10.1080/02827589509382887.

Laine, J., Vasander, H., Hotanen, J-P., Nousiainen, H., Saarinen, M., and Penttilä, T. 2012. Suotyypit ja turvekankaat—opas kasvupaikkojen tunnistamiseen. [Natural and drained peatland site types—a classification guide]. ISBN 978-952-5694-89-5. Metla, Helsingin yliopisto, Metsäkustannus, Metsäkustannus oy. 160p. [In Finnish].

Laurén, A., Palviainen, M., Launiainen, S., Leppä, K., Stenberg, L., Urzainki, I., et al. 2021. Drainage and stand growth response in Peatland forests—description, testing, and application of Mechanistic Peatland Simulator SUSI. Forests 2021, **12**: 293. doi:10.3390/f12030293.

Lehtonen, A., Aro, L., Haakana, M., Haikarainen, S., Heikkinen, J., Huuskonen, S., et al. 2021. Maankäyttösektorin ilmastotoimenpiteet: Arvio päästövähennysmahdollisuuksista. [Climate actions of the land use sector: an estimate of the possible emission reductions]. Luonnonvara- ja biotalouden tutkimus 65/2021, Luonnonvarakeskus, Helsinki. 122 s. [In Finnish].

Ménard, I., Thiffault, E., Kurz, W.A., and Boucher, J-F. 2023. Carbon sequestration and emission mitigation potential of afforestation and reforestation of unproductive territories. New For. **54**(2023): 1013–1035. doi:10.1007/s11056-022-09955-5.

Mikkelä, H., and Takamaa, H. 1995. Jaakkoinsuon kokeiluojitusalue—retkeilyopas. [Jaakkoinsuo experimental drainage area—a field guide]. Metsäntutkimuslaitos, Vantaan tutkimuskeskus. Painatuskeskus Oy, Helsinki 1995. ISBN 951-40-1486-3. 49p. [In Finnish].

Minkkinen, K., Ojanen, P., Penttilä, T., Aurela, M., Laurila, T., Tuovinen, J-P., and Lohila, A. 2018. Persistent carbon sink at a boreal drained bog forest. Biogeosciences, **15**(11): 3603–3624. doi:10.5194/bg-15-3603-2018.

Moilanen, M. 1993. Lannoituksen vaikutus männyn ravinnetilaan ja kasvuun Pohjois-Pohjanmaan ja Kainuun ojitetuilla soilla. [Summary: effect of fertilization on the nutrient status and growth of Scots pine on drained peatlands in northern Ostrobothnia and Kainuu]. Folia Forestalia 820. 37p.

Moilanen, M., and Issakainen, J. 1990. PK-lannos ja typpilannoitelajit karuhkojen ojitettujen rämeiden lannoituksessa. [Summary: PK fertilizer and different types of N fertilizer in the fertilization of infertile drained pine bogs]. Folia Forestalia 754. 20p.

Moilanen, M., Silfverberg, K., and Hokkanen, J. 2002. Effects of wood-ash on the tree growth, vegetation and substrate quality of a drained mire: a case study. For. Ecol. Manage. **171**(2002): 321–338. doi:10.1016/S0378-1127(01)00789-7.

Moilanen, M., Silfverberg, K., Hökkä, H., and Issakainen, J. 2005. Wood ash as a fertilizer on drained mires–growth and foliar nutrients of Scots pine. Can. J. For. Res. **35**: 2734–2742. doi:10.1139/x05-179.

Moilanen, M., Saarinen, M., and Silfverberg, K. 2010. Foliar nitrogen, phosphorus and potassium concentrations of Scots pine in drained mires in Finland. Silva Fenn. **44**(4): 583–601. doi:10.14214/sf.129.

Moilanen, M., Hytönen, J., and Leppälä, M. 2012. Application of wood ash accelerates soil respiration and tree growth on drained peatland. Eur. J. Soil Sci. **63**(4): 467–475. doi:10.1111/j.1365-2389.2012.01467.x.

Moilanen, M., Hytönen, J., Hökkä, H., and Ahtikoski, A. 2015. Fertilization increased growth of Scots pine and financial performance of forest management in a drained peatland in Finland. Silva Fenn. **49**(3): 1301. doi:10.14214/sf.1301.

Ojanen, P., Minkkinen, K., and Penttilä, T., 2013. The current greenhouse gas impact of forestry-drained boreal peatlands. For. Ecol. Manage. **289**(2013): 201–208. doi:10.1016/j.foreco.2012.10.008.

Ojanen, P., Penttilä, T., Tolvanen, A., Hotanen, J.-P., Saarimaa, M., Nousiainen, H., and Minkkinen, K. 2019. Long-term effect of fertilization on the greenhouse gas exchange of low-productive peatland forests. For. Ecol. Manage. **432**(2019): 786–798. doi:10.1016/j.foreco.2018.10.015.

Paarlahti, K., and Veijalainen, H. 1982. Leivonmäen Kivisuon metsänlannoituskokeet. [Leivonmäen Kivisuon metsänlannoituskokeet]. Metsäntutkimuslaitoksen tiedonantoja 306. 73p. [In Finnish].

Peltoniemi, K., Pyrhönen, M., Laiho, R., Moilanen, M., and Fritze, H., 2016. Microbial communities after wood ash fertilization in a boreal drained peatland forest. Eur. J. Soil Biol. **76**(2016): 95–102. doi:10.1016/j.ejsobi.2016.08.004.

Pinhero, J.C., and Bates, D.B. 2000. Mixed effects models in S and S-plus. *In* Statistics and computing. Springer, New York. 528p.

Pritchett, W.L., and Comerford, N.B. 1982. Long-term response to phosphorus fertilization on selected southeastern coastal plain soils. Soil Sci. Soc. Am. J. **46**(3): 640–644. doi:10.2136/sssaj1982.03615995004600030038x.

R Core Team. 2022. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available from https://www.R-project.org/ [accessed September 2023].

Rantala, T., and Moilanen, M. 1993. Nuorten suomänniköiden lannoituksen kannattavuus Pohjois-Pohjanmaalla [Summary: profitability of fertilization of young pine stands in northern Ostrobothnia]. Folia Forestalia 821. 20p.

Reinikainen, A., Veijalainen, H., and Nousiainen, H. 1998. Puiden ravinnepuutokset—Metsänkasvattajan ravinneopas. [A nutrient guide for a forester: nutrient deficiencies of trees]. Metsäntutkimuslaitoksen tiedonantoja 688. 44p. [In Finnish].

Serrano-León, H., Ahtikoski, A., Sonesson, J., Fady, B., Lindner, M., Meredieu, C., et al. 2021. From genetic gain to economic gain: simulated growth and financial performance of genetically improved *Pinus sylvestris* and *Pinus pinaster* planted stands in France, Finland and Sweden. Forestry, **2021**. 1–15. doi:10.1093/forestry/cpab004.

Shryock, B., Littke, K., Ciol, M., Briggs, D., and Harrsion, R. 2014. The effects of urea fertilization on carbon sequestration in Douglas-fir plantations of the coastal Pacific Northwest. Forest Ecol. Manage. **318**: 341–348. doi:10.1016/j.foreco.2014.01.040.

Sikström, U., Almquist, C., and Jansson, G. 2010. Growth of *Pinus sylvestris* after the application of wood ash or P and K fertilizer to a peatland in southern Sweden. Silva Fenn. **44**(3): 411–425. doi:10.14214/sf.139.

Silfverberg, K., and Moilanen, M. 2008. Long-term nutrient status of PK fertilized Scots pine stands on drained peatlands in North-Central Finland. Suo, **59**(3): 71–88.

Snowdon, P. 2002. Modeling type 1 and type 2 growth responses in plantations after application of fertilizer or other silvicultural treatments. For. Ecol. Manage. **163**(1–3): 229–244. doi:10.1016/S0378-1127(01)00582-5.

Trichet, P., Bakker, M.R., Augusto, L., Alazard, P., Merzeau, D., and Saur, E. 2009. Fifty years fertilization experiments on *Pinus pinaster* in southwest France: the importance of phosphorus as a fertilizer. For. Sci. **55**(5): 390–402.

Updegraff, K., Bridgham, S.D., Pastor, J., Weishampel, P., and Harth, C., 2001. Response of CO2 and CH4 emissions from peatlands to warming and water table manipulation. Ecol. Appl. **11**(2): 311–326. doi:10.1890/1051-0761(2001)011[0311:ROCACE]2.0.CO;2.

Veijalainen, H. 2000. Metsänparannuskokeiden tuloksia Kettulan tilan ojitetuilta soilta. [Results from forest improvement experiments in drained peatlands in Kettula]. Kettulan retkeily 8.9.2000. Moniste, Metla, Vantaan tutkimuskeskus 2000. 62 s. [In Finnish].

Vilén, T., Cienciala, E., Schelhaas, M.J., Verkerk, P.J., Lindner, M., and Peltola, H., 2016. Increasing carbon sinks in European forests: effects of afforestation and changes in mean growing stock volume. Forestry, **89**(1): 82–90. doi:10.1093/forestry/cpv034.

Westman, C.J., and Laiho, R. 2003. Nutrient dynamics of peatland forests after water-level draw-down. Biogeochemistry, **63**: 269–298. doi:10.1023/A:1023348806857.