Addition of Stabilized Wood Ashes to Swedish Coniferous Stands on Mineral Soils – Effects on Stem Growth and Needle Nutrient Concentrations

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Increasing use of forest fuels for energy production is generating increasing quantities of wood ash. A common understanding is that this ash should be spread in forests to counteract soil acidification and potential future nutrient deficiencies, and thus help sustain long-term forest productivity. A series of seven field experiments was established in Sweden in 1988–1995 to study the stem growth and needle nutrient concentrations of 30–60-year-old Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) stands on mineral soil after additions of wood ash in different doses or a combination of wood ash and N. The results showed that the most pronounced growth responses occurred when N was added, either alone or in combination with wood ash. The stem growth responses to additions of wood ash without N were small and variable, and not statistically significant at any of the studied experimental sites. However, there were indications that the addition of wood ash may increase stem-wood growth on fertile sites and decrease it on less fertile sites. In the short term, the addition of wood ash tended to increase the needle nutrient concentrations of most analyzed elements, except for N, but this could not be correlated to responses in stem growth.

Keywords foliar analysis, N fertilization, Norway spruce, *Picea abies*, *Pinus sylvestris*, recycling, Scots pine

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1 Introduction

During the last decade, interest in using logging residues for bioenergy production has increased in Sweden. In the district heating plant sector, the use of forest fuels (of which logging residues comprise an important proportion) has more than quadrupled since 1990 (Energy in Sweden 2000). Forest fuels, together with by-products from the forest industry, contribute 21% of the total energy used in Sweden (Energy in Sweden 2000). The use of forest fuels for energy production generates large amounts of wood ash, which at present are being dumped. The more intense biomass harvesting involved increases nutrient export from the forests, and soil acidification (Staaf and Olsson 1991, Olsson et al. 1993, Sverdrup and Rosén 1998). To prevent, or reduce, the negative effects of intensive biomass harvesting, it has been suggested that it would be of value to re-circulate the nutrients contained in the wood ash (Vance 1996, Olsson et al. 1996, Eriksson 1998). Wood ash has a high pH (ANC), and retains a major proportion of most macro-nutrients (except nitrogen (N)) and micro-nutrients from the biomass in an inorganic form.

Wood ash from forest industries and district heating plants is a very heterogeneous product. Differences in biomass fuels, combustion techniques and treatment of the ashes cause the wood ash to vary widely in solubility, nutrient concentrations, trace metal contents and in the other compounds present (Larsson and Westling 1998). Spreading loose (non-hardened) and highly soluble wood ash can cause rapid increases in the concentration of salts and the pH of the upper forest soil horizon (Khanna et al. 1994). Such ash may negatively affect the ground vegetation (Kellner and Weibull 1998, Jacobson and Gustafsson 2001), microfauna (Huhta 1984), mycorrhiza (Erland and Söderström 1991) and fine tree roots (Persson and Ahlström 1990, Clemensson-Lindell and Persson 1993, 1995). Furthermore, it has been shown that a pronounced increase in pH can increase nitrate leaching in N-rich soils (Hüttl and Zöttl 1993, Kreutzer 1995). In order to avoid this, it is advisable to transform the very reactive oxides of the initial ash into compounds with low solubility (e.g. carbonates), and to form larger aggregates with a dense, stable matrix, thus limiting contact with water around the ash particles.

The effects of adding wood ash on organic forest soils are well documented. On drained peatlands, addition of loose ashes normally induces a high and persistent increase in forest growth (Silfverberg and Huikari 1985, Silfverberg and Hotanen 1989). On mineral soils, the main purpose of adding wood ash is to counteract long-term nutrient depletion in the soil, rather than to obtain a short-term increase in forest growth. Prescott and Brown (1998) reported from British Columbia that an addition of wood ash (5 Mg ha^{-1}) to a N-limited 9-year-old plantation of western red cedar (*Thuja plicata* Donn ex D. Don) resulted in a significantly reduced height increment in the 5 years following addition. According to experience gained from forest liming experiments, the addition of an alkaline compound may influence the supply of inorganic N that is available for tree growth, and whether the effect is positive or negative is influenced by the N-status of the soil (e.g. Persson et al. 1991).

The main aim of this study was to determine whether the stem growth of coniferous trees on mineral soils is affected by adding stabilized wood ash in doses of 1 to 9 Mg ha^{-1}, or the combination of ash and N, and to test the hypothesis that the stem growth response is correlated with site fertility. An additional aim was to study, by means of needle analysis, whether these treatments affect the nutrient status of the trees.

2 Materials and Methods

2.1 Site and Stand Descriptions

Seven experimental sites were established in 1988–1995: four in Scots pine (*Pinus sylvestris* L.) stands and three in Norway spruce (*Picea abies* (L.) Karst.) stands, aged 35–65 years. The Scots pine experiments were distributed among sites with a wide range of climatic conditions and site fertility classes, whereas the three Norway spruce sites were all located in the south of Sweden, and on similar, high-yielding sites (Table 1). The soils were mainly deep, mesic tills, except

Table 1. Site and stand characteristics of the experimental sites at time of establishment.

	Norway spruce sites			Scots pine sites			
	182	241	244	183	242	250	251
Latitude	58°27´	56°55´	56°46´	57°10´	64°12´	59°48´	64°12´
Longitude	11°46´	13°05´	12°56´	14°50´	19°28´	15°30´	19°28´
Altitude (m a.s.l.)	120	135	140	210	230	135	155
Precipitation [a] (mm yr^{-1})	860	1190	1013	688	523	730	504
Annual mean temperature (°C) [a]	6.5	6.1	6.4	5.5	1.2	3.9	0.4
C:N in O-horizon [b]	27.7 [2]	25.5 [1]	25.0 [2]	29.5 [2]	31.5 [1]	32.5 [2]	44.3 [2]
Soil texture	Sandy-silty till	Sandy-silty till	Sandy-silty till	Sandy-silty till	Silt-sand	Sand	Sandy-silty till
Site quality (m^3 ha^{-1} yr^{-1})	12.0	11.3	12.0	7.7	6.4	5.9	4.3
Stand age (yrs)	35–60	40	65	35	40	50	60
Standing volume (m^3 ha^{-1})	280–340	250	450	160	160	150	160
Stems ha^{-1}	920–1550	1320	810	1380	1050	1100	1050
Study period (yrs) [c]	11	8	5	11	7	5	5

[a] Data from closest meteorological station according to Alexandersson et al. (1991).
[b] Data from: [1] Eriksson, H. (1998); [2] L. Högbom, SkogForsk, Uppsala, Sweden, pers.comm.
[c] Number of growing seasons between treatment and latest measurement.

Table 2. Treatments at the different experimental sites.

	Norway spruce sites			Scots pine sites			
Treatment	182	241	244	183	242	250	251
1 Mg wood ash ha^{-1} (1A)	x	x		x	x		
3 Mg wood ash ha^{-1} (3A) [a]		x	x		x	x [d]	x
6 Mg wood ash ha^{-1} (6A)		x			x	x	
9 Mg wood ash ha^{-1} (9A)						x	
150 kg N ha^{-1} (N)						x	x
2 ×10 kg N ha^{-1} yr^{-1} (N)			x				
1 Mg wood ash + 150 kg N ha^{-1} ($1AN_s$) [b]	x			x			
3 Mg wood ash + 150 kg N ha^{-1} ($3AN_s$) [b]		x			x	x	x
3 Mg wood ash + 150 kg N ha^{-1} ($3AN_a$) [c]		x			x	x	x

[a] At experimental site 244 the dose amounted 4.2 Mg ha^{-1}.
[b] Simultaneous addition of wood ash and N-fertilizer ($_s$ = simultaneous).
[c] Adding the wood ash after the N-granules had dissolved ($_a$ = after).
[d] In site 250 there were two treatments with 3 Mg wood ash ha^{-1}; crushed ash and pelleted ash.

for at two Scots pine sites (242 and 250) where the soils were glaciofluvial sediments.

2.2 Experimental Design and Treatment

All experimental sites were established as randomised block experiments with three replicates. The experimental plots were 30×30 m in size, except for plots in blocks 1 and 2 at site 182, in which the sizes were 24×24 and 23×23 m, respectively. Plots were arranged in blocks based on stand basal area and number of stems. Plots within a block were not allowed to deviate more than 5 and 10% from the block mean basal area and stem number, respectively.

The studied treatments consisted of wood ash in various doses, ranging from 1 to 9 Mg ha^{-1} (d.w.), together with combined ash and N treatments (Table 2). On some plots the combined ash and N treatment was performed by simultaneous addition of the two supplements, while on others the wood ash was added when the N-granules had dissolved. At experimental sites 241 and 242, the delay between the two additions in the combined treatment was nine months (September-May, i.e. mostly in the non-growing season). At experimental sites 250 and 251, the delay between the two additions was only one month (September). The N-dose was 150 kg ha^{-1}, added in the form

Table 3. Elemental concentrations of the wood ashes.

	Granulated ash 1 (sites 182, 183)	Granulated ash 2 (sites 241, 242)	Pelleted ash 1 (site 244)	Crushed ash (sites 250, 251)	Pelleted ash 2 (site 250)
LOI, %	53.0	4.5	25.2	8.7	33.6
Macro elements, [mg (g DM)$^{-1}$]					
N	<0.1	<0.1	4	<0.1	<0.1
Ca	100	140	270	137	152
Mg	9	15	17	14	14
K	52	41	31	64	35
P	9	8	12	8	8
Al	23	46	17	19	31
Mn	7	7	n.d.	8	1
S	n.d.	n.d.	3	11	2
Si	84	240	83	56	94
Trace elements, [µg (g DM)$^{-1}$]					
As	5	5	n.d.	9	15
Pb	63	21	125	108	70
Cd	21	6	2	12	9
Cu	99	24	300	108	104
Cr	108	75	40	56	54
Ni	48	28	n.d.	114	39
Zn	2030	1006	535	3360	3990
V	32	56	n.d.	77	37
Hg	0.3	0.3	n.d.	0.3	0.9
B	200	132	232	304	138

n.d. = not determined.

of ammonium-nitrate (N 34.5%) at experimental sites 182 and 183, and in the form of dolomite-ammonium-nitrate (N 27.5%, Ca 4.0%, Mg 1.0% and B 0.2%) at sites 241, 242, 250 and 251. At site 244, the N treatment consisted of annual additions of 20 kg ha^{-1} yr^{-1}, (ammonium-nitrate), split between two occasions.

2.3 The Wood Ashes

Various ashes were used, which differed both in origin and constitution. The first type of ash granules (used at sites 182 and 183) had a high C content, and the loss on ignition was as high as 53%. When transforming the loose ash into granules, calcium-ligno-sulfonate and cement were added (both to 1%). Despite this, the resulting granules were soft and porous. The second ash granule type (used at sites 241 and 242) was well-combusted with a loss on ignition of 4.5%. Cement was added (4%) during the granulation process, and the resulting granules were hard and compact. The diameter of the granules varied between 5 and 20 mm.

So-called "crushed ash" was used at experimental sites 250 and 251. This ash was moistened by adding ca. 30% H_2O (w/w) and allowed to harden naturally over a period of one month in the summer, before being crushed and screened. The ash particles thus formed appeared to be hard and compact. The content of fine particles (< 0.25 mm) was 15%. The coarse particle fraction (2.0–10.0 mm) amounted to c. 60% of the total. However, a laboratory test performed later showed that the curing process had been incomplete, as a large part of the crushed ash was easily dissolved in water. The ash was thus quite reactive.

The first type of pelleted ash (used at site 244) was produced after mixing with water and compost (c. 15% by weight). Thus, this ash product contained some N (4.3 mg g^{-1} by weight). During the production of the second type of ash pellets (used at site 250, 3 Mg ha^{-1}), pine oil was added (to 8–10%) to act as a binding agent. The different pellets used were 5–7 mm in diameter and 5–30

Table 4. Needle sampling schedules at the experimental sites.

	Sampling year											
	0 [a]	1	2	3	4	5	6	7	8	9	10	11
Norway spruce sites												
182		x	x	x		x						x
241		x	x	x	x	x		x				
244	x	x	x					x				
Scots pine sites												
183		x		x		x						x
242		x	x	x	x	x		x				
250	x	x	x	x	x	x						

[a] Needles sampled the year before treatment.

mm in length.

The chemical composition of the ashes is detailed in Table 3. Ca, Mg, K, P, Al, Mn and Si were determined by ICP-AES after being fused with $LiBO_2$ and dissolved in dilute HNO_3. Trace elements were determined by ICP-MS after digestion by microwave heating in closed teflon vessels with $HF/HNO_3/HCl$ (1:3:1 by volume).

2.4 Stem Growth

All growth measurements were taken in a circular area at the centre of each plot, with a radius of 10 m (except for blocks 2 and 3 at site 182, in which the radii were 7 and 6.5 m, respectively). At the time of establishment, all trees with a diameter >5 cm at breast height (1.3 m above ground) were permanently numbered and measured. The measurements taken included diameter at breast height (dbh, mm), determined by cross-callipering at permanent marks on the stem, and height of the trees (dm). At the end of the study period (5–11 yrs, Table 1), the measurements were repeated and increment cores were taken with a borer at breast height. The annual growth ring widths were measured under a microscope with an accuracy of ± 0.01 mm. The volume of individual trees was estimated using empirical functions provided by Näslund (1947).

Thinning operations were performed during the experimental period at experimental sites 182, 183 and 250, (five, four and two years after treatment, respectively). The grade of thinning varied between the different sites (13–27% of the basal area), but was approximately the same on all plots within each block of a site. The removed trees were measured in the same way as the standing trees at revision, and the actual measured growth up to thinning time of these trees was included in the growth analyses. Tree mortality in the experiments was negligible. For trees that died during the experimental period, the growth they would have displayed was estimated by assuming that it would have been similar to the growth of live trees with a similar diameter in the same plots.

2.5 Needle Sampling and Analyses

Current-year needles were sampled with varying intensity in six experimental sites (Table 4). Samples were collected during the winter (December–March) from 10 trees growing immediately outside each circular plot. Twigs from the upper third of the crown on the south side were shot down with a shotgun using steel bullets. The needles from the ten trees representing each plot were pooled into single samples, which were then dried overnight at 70ºC, ground and mixed thoroughly. The needle concentrations of P, K, Ca, Mg, Mn, S, Na, Fe, Zn, Al, B and Cu were determined by ICP-AES, after wet oxidation in a mixture of concentrated HNO_3 and $HClO_4$ (10:1 by volume). Nitrogen concentrations were in most cases determined in a NA 1500 elemental analyser (Carlo-Erba), but for samples from experimental sites 182 and 183, N was determined according to Kjeldahl.

2.6 Statistical Analyses

Treatment effects on total stem-volume increment (VI), and nutrient concentrations of the needles (NC) in individual years, were tested using analysis of variance. For basal area increment (BAI) and VI, several variables related to stand properties were tested as covariates to adjust for differences in pre-treatment conditions. The covariates basal area increment during the five years before treatment (BAI_{-5}), initial stand basal area (BA_0), initial stand volume (V_0) and number of stems per hectare (ST_{ha}) were tested and included in the model if the respective *p*-values were less than 0.20. Furthermore, log-transformed NC values of the individual experiments were pooled together and analysed annually by tree species in a mixed model.

The following models were used for the individual experiments:

$$y_{jk} = \mu + u_j + t_k + b(g_{jk} - \bar{g}) + e_{jk} \qquad \text{(Eq. 1)}$$

and for the pooled NC data by species:

$$y_{ijk} = \mu + l_i + u_{j(i)} + t_k + (l \times t)_{ik} + e_{ijk} \qquad \text{(Eq. 2)}$$

where

y_{jk}, y_{ijk} = BAI, VI or NC for plot *jk* or *ijk*
μ = Total mean
l_i = Random effect of experimental site *i* (*i* = 1,…, *n*; *n* = 4 (pine) or *n* = 3 (spruce))
u_j, $u_{j(i)}$ = random effect of block *j* (*j* = 1,2,3 or block *j(i)*)
t_k = fixed effect of treatment *k* (*k* = 1,…, *n*; *n* =2–8)
b = coefficient for the regression of the covariate
g_{jk} = the covariate variable for plot *jk*
e_{jk}, e_{ijk} = residual effect for observation *jk* or *ijk*, N.I.D. $(0, \sigma_e^2)$

The need for transformation was judged by the Shapiro-Wilk test, kurtosis, skewness and visual interpretations of the residuals in normal-probability plots. In the analyses of the pooled NC data, the normal distribution of the residuals were generally improved after a logarithmic transformation. The General Linear Model procedure of the SAS-package (SAS 1997) was used for the statistical analyses of the individual experimental sites. The NC data, pooled by tree species, were analysed using the SAS Mixed Model procedure (cf. Littell et al. 1996), with l_i and $(l \times t)_{ik}$ regarded as random effects, and the estimated treatment effects were corrected for logarithmic bias. Differences between treatment means were tested according to the Tukey-Kramer method. In addition, linear regression analyses were used in an attempt to test the hypothesis that the growth response to wood ash addition is correlated with site fertility. The relative stem growth response, i.e. the average response to all treatments in which ash alone was added, at each experimental site, was set as dependent variable, and site quality ($m^3\ ha^{-1}\ yr^{-1}$) or C to N ratio in the humus layer as independent variable.

3 Results

3.1 Stem Growth

The volume growth response to the addition of wood ash was small, variable, and statistically insignificant ($p > 0.05$) at all doses and at all experimental sites. The most marked increase was observed at site 182 (Norway spruce), where the volume growth response, after addition of 1 Mg of wood ash ha^{-1}, averaged 1.2 $m^3\ ha^{-1}\ yr^{-1}$ ($p = 0.06$) during the 11-year study period. At the more fertile sites, i.e. the three Norway spruce sites and the most southerly Scots pine site (183), the development of the annual relative BAI indicated a slight increase in growth after wood ash treatment (Fig. 1), and the average effect of wood ash addition per site was a 4–10%, non-significant increase in stem-volume growth (Table 5). At the three less fertile Scots pine sites, i.e. site 250 in the central part and sites 242 and 251 in the northern part of Sweden, the annual BAI values were most frequently lower than the values of the control plots (Fig. 1), and the average effect of wood ash addition per site was a 3–8% non-significant reduction in stem-volume growth (Table 5). Linear regression indicated that the relative stem growth response after wood ash addition (i.e. the mean value for all doses in each experimental site) was positively correlated to site quality (R^2=0.70; p_{slope} = 0.02) and tended to be negatively correlated to the C to N ratio in the humus

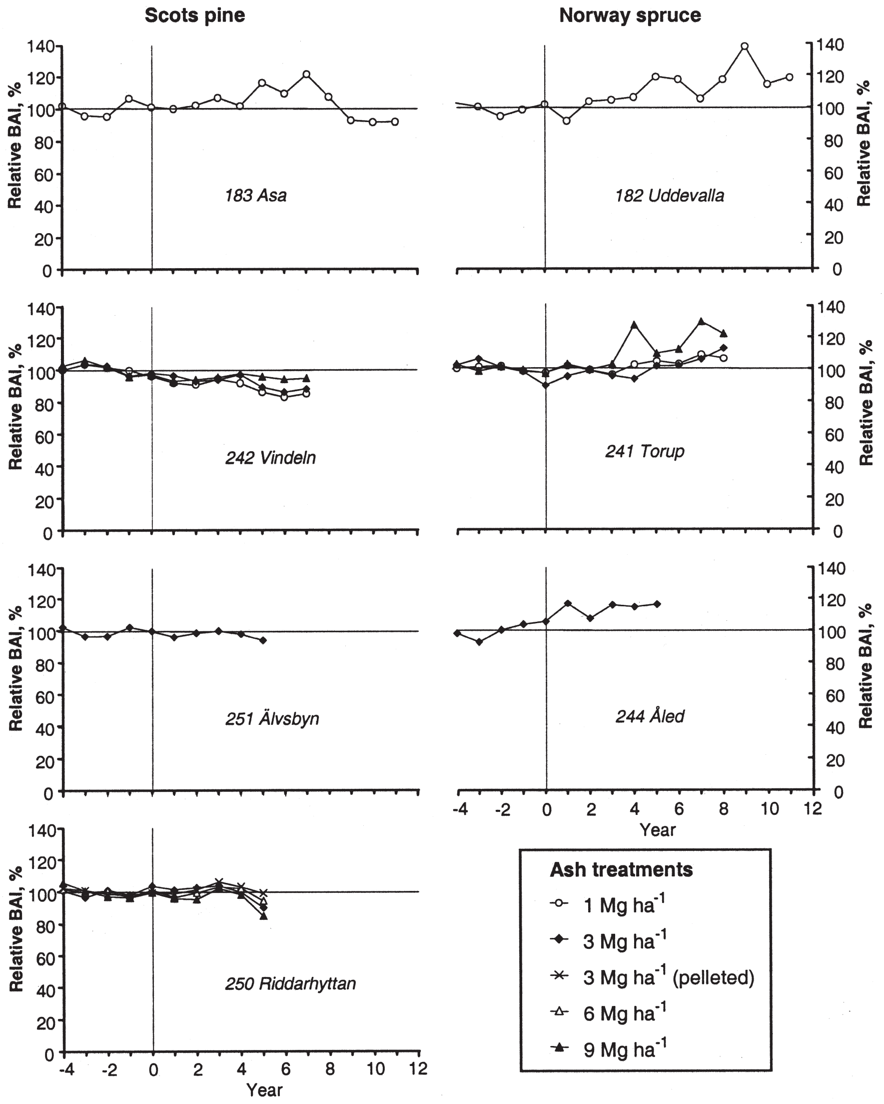

Fig. 1. Annual relative basal area increment (BAI) for the different ash treatments in relation to untreated control plots (100%). Adjusted for pre-treatment growth rates.

layer (R^2=0.51; p_{slope} = 0.07).

At all experimental sites, the most pronounced growth responses were obtained when N was added, either alone or in combination with wood ash. Statistically significant ($p < 0.05$) increases in volume increment occurred at four sites (Table 5). At the two sites (250 and 251) where comparisons were possible, no difference in growth response was found between the combined N + wood ash and N alone. Neither, at three out of four sites, did the growth response to the simultaneous addition of wood ash and N-fertilizer significantly differ from the response to adding the two supplements on separate occasions. At the fourth site (242), the volume increment was significantly higher ($p < 0.05$) when the wood ash was added nine months after the N addition, compared to the treatment with simultaneous addition.

Table 5. Annual stem-volume increment in absolute (m^3 ha^{-1} yr^{-1}) and relative (percent of control growth; *in parenthesis*) terms, associated with the different treatments at the seven experimental sites. Values in the same column marked with different letters differ significantly ($p < 0.05$, according to Tukey-Kramer's test for multiple comparisons).

	Norway Spruce sites			Scots pine sites			
Treatment	182	241	244	183	242	250	251
p-value, treatment	0.02	0.05	0.49	0.06	<0.01	<0.01	<0.01
Control	15.0 a	11.4	11.3	10.2	10.7 a	6.9 a	4.4 a
	(100)	(100)	(100)	(100)	(100)	(100)	(100)
1A	16.2 a	11.6		10.8	9.3 a		
	(108)	(102)		(107)	(87)		
3A		11.6	12.4		10.3 a	6.7 a	4.2 a
		(102)	(110)		(96)	(97)	(94)
3A [d]						7.1 a	
						(103)	
6A		12.3			10.0 a	6.8 a	
		(108)			(94)	(99)	
9A						6.2 a	
						(90)	
N [a]			13.1			10.7 b	7.2 b
			(116)			(155)	(164)
1AN$_s$ [b]	17.8 b			11.4			
	(119)			(112)			
3AN$_s$ [b]		12.7			10.8 a	11.0 b	6.8 b
		(111)			(101)	(160)	(153)
3AN$_a$ [c]		12.8			12.3 b	11.0 b	7.2 b
		(112)			(115)	(160)	(162)
Contrasts [e]							
All ash alone	1.2	0.5	1.1	0.6	–0.8	–0.2	–0.2
treated plots	(8%)	(4%)	(10%)	(7%)	–8%	–3%	–6%
versus control	*p*=0.06	*p*=0.23	*p*=0.56	*p*=0.11	*p*=0.06	*p*=0.38	*p*=0.52

[a] 150 kg N ha^{-1}, single shot addition (sites 250 and 251); 2 ×10 kg N ha^{-1} annually (site 244).
[b] Simultaneous addition of wood ash and N-fertilizer.
[c] Adding the wood ash after the N-granules had dissolved.
[d] Pelleted wood ash.
[e] Volume increment differences. Relative effects within brackets.

3.2 Nutrient Concentrations in Needles

The nutritional status of the current-year needles varied somewhat between the experimental sites (Table 6). At all the sampled sites, the N, P and K concentrations were consistently lower than the optimum levels (as defined by Brække 1994, Brække et al. 1998). The Ca and Mg concentrations, as well as the concentrations of the analysed micronutrients (data not shown), were all above the proposed optimum levels.

Significant (p<0.05) treatment effects for the data pooled with respect to individual tree species, were only found when N had been added, and only at Scots pine sites. The N concentration increased when N was added, alone or together with wood ash, and the K concentration increased in the combined N+wood ash treatment (Table 7). The addition of wood ash tended to increase the concentrations of many analysed elements, and significantly for K and B (Figs. 2–3).

Table 6. Nutrient concentrations [mg (g DM)$^{-1}$] in current-year needles on untreated control plots. Means of four (sites 183 and 244), five (site 182) and six (sites 241, 242 and 250) years of sampling. Critical concentrations for strong deficiency and optimum nutrition, according to figures suggested by Brække (1994, revised in Brække et al. 1998).

Element	Norway spruce sites			Scots pine sites			Critical concentrations	
	182	241	244	183	242	250	Strong deficiency	Optimum
N	13.9	12.4	14.6	13.7	12.6	12.0	<12.0	>18.0
P	1.3	1.5	1.3	1.5	1.5	1.3	<1.2	>1.8
K	4.7	4.3	5.4	4.7	4.9	5.0	<3.5	>6.0
Ca	4.3	2.3	2.5	2.2	2.2	1.8	<0.4	>0.7
Mg	1.3	1.3	1.1	1.0	1.2	0.9	<0.4	>0.8

Table 7. Nutrient concentrations [mg (g DM)$^{-1}$] in current-year needles at the experimental sites analysed by tree species; 1–2, 3–5 and 7–11 years after treatment. Values in the same row marked with different letters differ significantly ($p < 0.05$; according to Tukey-Kramers's test for multiple comparisons). No significant site × treatment interaction was detected.

Element	Year	Treatment					*p*-value, treatment
		0	1–3 A	6–9 A	1–3 AN	N	
Norway spruce sites							
N	1–2	13.6	13.8	13.8	15.2	–	0.36
	3–5	13.1	13.2	13.5	13.7	–	0.61
	7–11	13.0	12.9	12.9	12.7	–	0.52
P	1–2	1.36	1.44	1.61	1.33	–	0.28
	3–5	1.36	1.33	1.45	1.22	–	0.55
	7–11	1.31	1.29	1.47	1.15	–	0.07
K	1–2	4.70	5.21	5.54	5.70	–	0.22
	3–5	4.69	5.58	5.27	5.20	–	0.27
	7–11	4.77	5.05	5.41	5.49	–	0.38
Ca	1–2	2.89	2.90	3.08	2.87	–	0.97
	3–5	3.37	3.20	3.45	3.31	–	0.97
	7–11	2.83	3.09	3.44	3.31	–	0.72
Mg	1–2	1.18	1.25	1.26	1.16	–	0.53
	3–5	1.41	1.35	1.36	1.34	–	0.81
	7–11	1.22	1.34	1.32	1.35	–	0.24
Scots pine sites							
N	1–2	12.7 a	13.1 a	12.9 a	15.8 b	15.6 b	<0.01
	3–5	12.6 a	12.5 a	12.4 a	14.0 b	14.4 b	<0.01
	7–11	13.5	13.0	14.0	13.0	–	0.34
P	1–2	1.45	1.48	1.52	1.53	1.57	0.54
	3–5	1.44	1.52	1.50	1.62	1.66	0.12
	7–11	1.57	1.56	1.60	1.55	–	0.98
K	1–2	4.98	5.14	5.05	5.29	4.88	0.54
	3–5	4.83 a	5.07 ab	5.23 ab	5.40 b	5.09 ab	0.01
	7–11	4.78	4.89	4.68	4.92	–	0.83
Ca	1–2	2.28	2.62	2.50	2.44	2.45	0.44
	3–5	1.94	2.17	2.06	1.81	1.97	0.06
	7–11	2.22	2.28	2.57	1.72	–	0.19
Mg	1–2	1.07	1.06	1.08	1.04	1.00	0.77
	3–5	1.03	1.00	1.05	1.01	1.07	0.31
	7–11	1.18	1.05	1.21	1.05	–	0.24

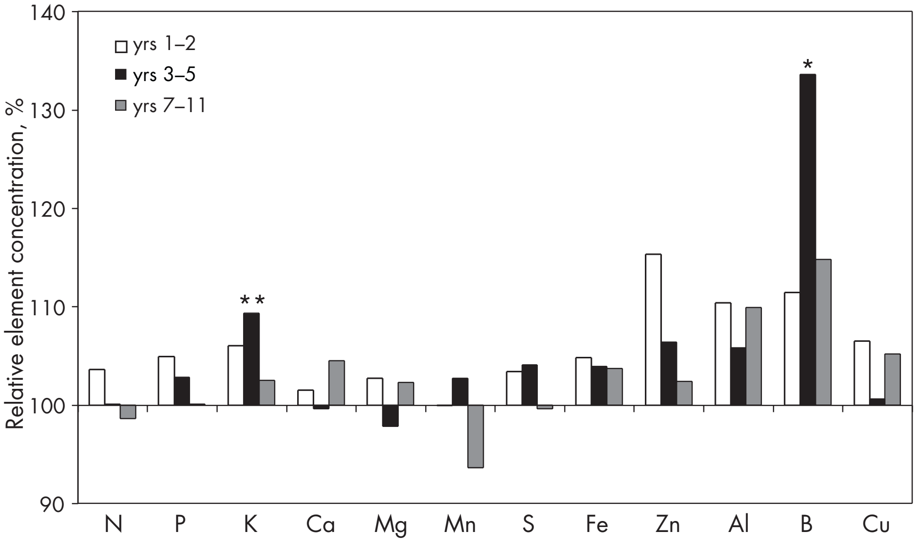

Fig. 2. Relative elemental concentrations in current-year needles, in relation to untreated control plots (100%), during different periods after wood ash addition. Mean values for all plots treated with ash alone at all experimental sites. Levels of significance compared with untreated control: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, according to LSD-test.

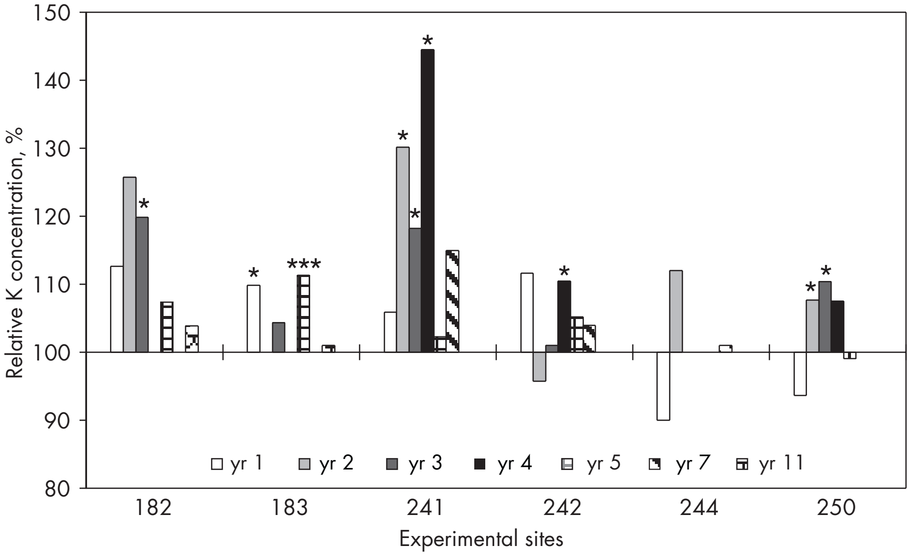

Fig. 3. Relative K concentrations in current-year needles, in relation to untreated control plots (100%), at each experimental site at different years after wood ash addition. Mean values for all plots treated with ash alone. Levels of significance compared with untreated control: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, according to LSD-test.

4 Discussion

The results for the individual experimental sites showed that the addition of wood ash did not significantly affect stem growth. There were also indications (although not statistically significant) that the addition of wood ash may increase stem-wood growth on fertile sites and decrease growth on less fertile sites. When pooling the growth data from the four most high-yielding sites, located in the southern parts of Sweden, and treating the different ash doses as one treatment, there was a significant ($p = 0.02$) growth increase (0.8 m^3 ha^{-1} yr^{-1}, or 7%) compared to the controls. The corresponding figure for the three less fertile Scots pine sites was a non-significant ($p = 0.18$) reduction in growth of 0.4 m^3 ha^{-1} yr^{-1} (6%). These analyses may however be questioned, since the grouping of data is based, to some extent, on subjective selection among the samples. Nevertheless, since the conclusions are supported by results from the regression analyses, the hypothesis that the response is positively correlated with site fertility seems valid.

The number of experimental sites is small, and the observation period needs to be extended. Furthermore, the differences in the lengths of the observation periods, and in the types of ash applied, between experimental sites complicate interpretation of the data. Nevertheless, the results obtained from this study so far are consistent with experience gained from liming (cf. Andersson et al. 1996). Despite the anthropogenic input, N is still the growth-limiting nutrient for the vast majority of the Swedish forests (Pettersson 1994, Binkley and Högberg 1997), and the addition of wood ash probably influences the supply of inorganic N that is available for tree growth. The addition of wood ash to the fertile sites with N-rich forest soils, such as moder/mull soils, probably increased the net rate of mineralization of N in the soil organic layer, while in the more N-poor forest soils it probably led to an increase in N-immobilization. The C to N ratio in the humus layer has been suggested as an indicator that could be used to judge whether a pH increase in the soil leads to increased or decreased rates of net mineralization. According to a rough rule-of-thumb, based on data gathered from forest liming experiments, increases in net mineralization occur after liming if the C to N ratio in the humus layer is less than 30 (Nömmik 1968, Persson 1988). Thus, the tendency found in this study for the C to N ratio to be negatively correlated to the relative growth response following addition of wood ash is in agreement with findings from the liming studies.

Moreover, according to Persson and Wirén (1996), the addition of an alkaline compound to N-rich soil ($C:N < 28$) may result in increased rates of nitrification and NO_3^- leaching, and the pools of total N in soil have been reported to decline after liming fertile sites (Kreutzer 1995, Persson et al. 1995). These observations imply that N availability falls in the long term at limed fertile sites. Increased concentrations of NO_3^- in the soil solution after addition of wood ash have been reported from the fertile experimental site 244 (Högbom et al. 2001).

At the four most fertile sites, stem-volume growth tended to increase after wood ash addition. However, at site 241, only the largest ash dose (6 Mg ha^{-1}) seemed to enhance growth, while at site 182 and 183 the trees seemed to respond to the low dose (1 Mg ha^{-1}). These differences in dose responses may be due to disparities in the length of the observation period, and/or differences in the chemical and physical constitution of the wood ashes added. It is conceivable that the porous ash-granules added at sites 182 and 183 had a more rapid influence on N-mineralization, when compared to the firm and compact granules used at site 241.

The largest growth responses at all experimental sites were obtained when N was added alone or in combination with wood ash, indicating N-limitation. At two of the Scots pine sites (sites 183 and 242), the growth responses of the combined treatments were smaller than expected, according to predictive functions for N fertilization on mineral soils in Sweden (Pettersson 1994). At site 183, in an earlier study performed in the same stand, the addition of 150 kg N ha^{-1} resulted in a significant increase (28%) of the stem basal area (Sikström, 1997). The insignificant N-effects on growth at the Norway spruce sites studied were not unexpected. The response at these fertile sites, with moder/mull soils and no (or very thin) eluvial horizons, is often small and very variable

(Jacobson and Pettersson 2001). So, N fertilization on these types of site is not recommended in practical forestry in Sweden (Pettersson 1994). At site 241 (Norway spruce), where no N treatment was applied without the addition of wood ash, the possibility that N was the primary growth-limiting nutrient is a matter for speculation. However, the relatively low N-concentration in needles (12.4 mg g^{-1}) indicate N-limitation also at this site.

Due to the high pH of the wood ash there is an increased risk of ammonia formation when simultaneously adding an ammonium-nitrate fertilizer. Thus, a possible explanation for the apparent lack of a growth response when adding wood ash and N on the same occasion, as observed at the Scots pine site 242, is that there was a loss of N through ammonia volatilization. Ammonia volatilization could also provide an explanation for the poor N response to the combined treatment at site 183. However, at three other sites (sites 241, 250 and 251) there were no significant differences in growth responses when comparing the two combined treatments. Still, the possibility that ammonia volatilization occurred at these sites cannot be dismissed, since it depends on the weather conditions prevailing at the time of spreading (Nömmik 1973, Melin 1986). The poor growth response to the N added at site 241 may have been due to the N dose (150 kg ha^{-1}) being greater than optimal for growth (in which case potential N loss via ammonia volatilization would not have reduced the growth response). Also, since the period between the N addition and the addition of wood ash was only one month at sites 250 and 251 (compared to nine months at sites 241 and 242), it is conceivable that the risk of ammonia volatilization was not totally avoided at sites 250 and 251.

The addition of wood ash tended to increase the concentrations of most analysed elements. Among macronutrients, there was a significant ($p < 0.01$) increase in K concentrations in the middle of the study period. However, the results also imply that the elevated K concentrations were short-term (Figs. 2–3). As argued by Carter (1992), conclusions about the nutrient status of sites cannot be based solely on foliar nutrient concentrations, but should also be related to stand growth performance and site characteristics. The growth performance of the stands in this study implies that a shortage of N limited primary production at all the studied sites. The fact that the P and K concentrations in the needles were below the suggested optimal levels (as defined by Brække 1994), does not necessarily mean that these elements were growth limiting. According to the law of limiting factors (Liebig's principle), it merely gives an indication that one of these elements may become limiting at the point where N ceases to limit primary production. The elevated concentrations of K and B found to occur after wood ash addition in this study must be regarded as symptoms of "luxury" uptake. From this perspective, and from the forest stand growth point of view, the concept of "recycling" the wood ashes must be regarded as a preventive action against possible nutrient imbalances in the future. However, the utility of such preventive action can be questioned, as it presupposes a long-term capacity of the ecosystem to retain the nutrients added in available forms.

Recycling wood ash has been proposed as a method to compensate for the nutrient removals that occur during whole-tree harvesting (Olsson et al. 1996, Eriksson 1998), and to thus sustain future forest productivity (Clarholm 1994, Sverdrup and Rosén 1998). During the relatively short study period (5–11 years), the insignificant results obtained in this investigation imply that the nutrients supplied with the ash did not promote growth. Nevertheless, on fertile sites, the results indicate that an addition of wood ash may, at least temporarily, compensate for the growth reductions that normally follow whole-tree harvest, presumably due to its effects on soil N turnover. However, increased amounts of available N at these sites also imply an increased risk of nitrate leaching, which in the long-term may decrease N-availability. On less fertile sites, addition of N is a prerequisite to counteract the reductions in growth.

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