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Wood Ash Application in Spruce Stands

Effects on ground vegetation, tree nutrient status and soil chemistry

Helen Arvidsson

SWEDISH UNIVERSITY OF AGRICULTURAL SCIENCES

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Abstract

In order to decrease the use of fossil fuels and to reduce the emissions of greenhouse gases, plant biomass can be used as an energy source. In Sweden, logging residues from forest harvesting form a biomass resource that will presumably be increasingly used in the future. It is recommended that the wood ash from large-scale biomass burners should be returned to the harvested site in order to minimize the risk of soil acidification and depletion of base cations due to intensive harvesting. This thesis summarizes the results from four studies examining the effects of wood ash on ground vegetation, tree nutrient status, soil and soil water chemistry.

The experimental sites used in the thesis were 1-4 year old Norway spruce (*Picea abies* (L.) Karst.) stands within a fertility gradient that was replicated along a climate gradient. At each site, 3000 kg ha^{-1} crushed wood ash was applied in a randomized block design. The effects of wood ash application on the ground vegetation composition or cover were limited. The bryophytes showed no visible negative response to the ash application. The concentrations of P, K and Ca in the needles were higher in wood ash treated plots than in control plots. The needle concentrations of Mg and S were not affected by the ash applications. Wood ash application generally resulted in modestly but significantly increased concentrations of exchangeable Ca and Mg and CEC. The effects were most pronounced in the upper 0-5 cm layer. In the upper 5 cm of the soil, pH increased by on average 0.6 pH units in wood ash treated plots compared to control plots. Base saturation increased in the whole soil profile. Addition of wood ash did not affect the concentration of NO_3-N in the soil water at 50 cm depth below the soil surface.

The conclusion I was able to draw from these studies was that a compensatory dose of crushed wood ash can be applied to young Norway spruce stands without any detrimental effects on forest plants or increased concentrations of nitrate in the soil water below the rooting zone. Wood ash application would most likely compensate for nutrients removed at intensive harvesting. This is an important aspect for the potential to maintain long-term forest production under sustainable nutritional conditions, even with intensive forest management.

Key words: ground vegetation biomass, cations, chemistry, clear-felling, *Picea abies*, forest soil, needle analyses, nutrients, species composition, species cover, whole-tree harvesting.

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Contents

Appendix

Papers I-IV

This thesis is based on the following papers, which will be referred to by their Roman numerals:

I. Arvidsson, H., Vestin, T. and Lundkvist, H. 2001. Effects of crushed wood ash application on ground vegetation in young Norway spruce stands. *Forest Ecology and Management* (in press).

II. Arvidsson, H. and Lundkvist, H. Needle chemistry in young Norway spruce stands after application of crushed wood ash. (accepted for publication in *Plant and Soil*).

III. Arvidsson, H. and Lundkvist, H. Effects of crushed wood ash on soil chemistry in young Norway spruce stands. (submitted to *Forest Ecology and Management*).

IV. Arvidsson, H. and Lundkvist, H. Wood ash application to young Norway spruce stands shortly after clearfelling - Effects on soil water chemistry. (manuscript).

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Introduction

The concentration of atmospheric carbon dioxide is currently increasing, with the overall increase being largely due to the burning of fossil fuels. The greenhouse gas that makes the largest contribution to the potential global warming effect is CO_2 (Schlesinger, 1997). Replacing fossil fuels with biomass is a key strategy in reducing the CO_2 emissions. Biomass is a CO_2-neutral energy source provided that new biomass is grown in replacement of what has been harvested. In Sweden the use of biomass for energy has the potential to increase significantly (Hektor et al., 1995; Börjesson et al., 1997).

The total energy use in Sweden in 1999 was 615 TWh calculated in accordance with the international method of energy accounting, which includes the energy conversion losses in nuclear power stations (Anon., 2000). The supply to the total 1999 energy use in Sweden from crude oil and oil products was approx. 200 TWh, from nuclear power 206 TWh (68 TWh of electricity) and from hydro power about 68 TWh. The use of biofuels amounted to 94 TWh. The biofuels were mainly indigenous and consisted of wood fuels, black liquors from pulp mills, peat (included in the concept of bioenergy), short rotation willow plantations ("energy forest") and refuse. The biofuels were mainly used in the forest industry, district heating plants and within private houses. The 1999 contribution to the total energy use from short rotation willow plantations was about 0.1 TWh, from the use of peat 3 TWh and from refuse 5 TWh, which means that 86 TWh of the biofuel had its origin from forestry. The forest products industry uses the by-products from various processes for the production of heat and electricity. Felling residues (branches and tops) and forest by-products such as wood chips and bark accounted for the main fuel used for heat production in the district heating sector.

In Sweden, felling residues are collected and removed from approx. 20% of the total final felling area (Anon., 2001a). Increased harvesting of felling residues from the forest will result in increased nutrient export from the forest compared with stem-wood harvest only. This may cause nutrient imbalances in forest trees (Olsson et al., 2000) and there is a risk for depletion of base cations in forest soils (Olsson et al., 1993; Olsson et al., 1996; Svedrup and Rosén, 1998). In order to counteract these negative effects, wood ash from district heating plants and the forest industry will have to be recycled to forest sites. Wood ash recycling has been suggested as a means to counteract several negative effects of more intense harvesting systems like whole-tree harvesting, i.e. harvesting all above-ground parts of the tree (Olsson et al., 1996; Eriksson, 1998). Lundborg (1998) concluded that with recycling of wood ash, it would be possible to use more intense harvesting systems without compromising the environmental status. Thus, provided that current guidelines for forest management methods are followed, including leaving old trees, leaving dead wood and paying particular attention to valuable biotopes, harvesting of felling residues could be carried out on a large scale without causing any conflict with nature conservation (Lundborg, 1998).

Some of the concerns raised as regards recycling of wood ash to forest soil involve the pH raising effect of the ash. An increase in soil pH has been shown to enhance nitrate leaching in some cases (Khanna et al., 1994; Kahl et al., 1996; Williams et al., 1996). Bramryd and Fransman (1995) reported an increase of approx. 1 pH unit in the mor layer 10 years after application of loose ash in a dose of 2000 kg ha^{-1}. However, compared to loose, untreated wood ash, stabilized wood ash has been shown to cause a less drastic pH effect on the soil (Eriksson et al., 1998; J. Eriksson, 1998; Eriksson, 1998). Stabilization is carried out with the aim of decreasing the solubility of the ash through the formation of denser and bigger ash particles. Stabilized ash products are granulated, crushed or pelletized wood ash, see below.

Decreased soil acidity and increased base saturation following application of wood ash have been reported (Unger and Fernandez, 1990; Khanna et al., 1994; Bramryd and Fransman, 1995; Kahl et al., 1996; Levula et al., 2000). The effects of application of wood ash to forest soil depends on the properties of the ash, the type of soil in question and the interaction between the soil and the wood ash. Application of loose wood ash in high doses to drained peatlands has produced beneficial effects in terms of a long-lasting increase in growth of Scots pine and an increase in N, P and K levels in the needles (Silfverberg and Hotanen, 1989). However, application of 3000 kg ha^{-1} loose wood ash to a Scots pine stand on mineral soil showed no effect on needle nutrient concentration one year after application (Vuorinen and Kurkela, 2000). No effect on needle nutrient concentrations was found four years after application of a granulated wood ash to a forest soil at a dose of 3200 kg ha^{-1} (Rosengren-Brinck, 1994).

Field experiments with applications of loose wood ash have been established in the past (Romell and Malmström, 1945). These experiments were often conducted on peatland (see also overviews by Linder (1990) and Bramryd and Fransman (1985)). Establishment of replicated field experiments with wood ash applications on mineral soil started in the 1920s (Nohrstedt et al., 1999). An Environmental Impact Assessment of the utilization of forest fuel and wood ash recycling has been made in order to evaluate the research done and to identify gaps in existing knowledge (Egnell et al., 1998). Egnell et al. (1998) concluded that a major proportion of the potentially available logging residues could be used provided that losses of nutrients and acid neutralizing capacity were compensated for. They also concluded that leaving the needles well distributed at the site could decrease the negative impacts of harvesting logging residues and that wood ash application should not be carried out within five years before or after clearcutting. Due to lack of knowledge about long-term effects on biological processes in the soil and on soil organisms, a certain area should be set aside and not used for harvesting of logging residues or wood ash application (Egnell et al., 1998).

Wood ash chemistry

The annual production of pure wood ash in Sweden has been estimated to be between 100 000-150 000 tonnes (Åbyhammar et al., 1994). The properties of an ash material are mainly determined by the fuel and the combustion method used (Etiégni and Campbell, 1991, Someschwar, 1996). The composition of an ash also depends on the type of boiler. Wood contains small amounts of ash, 0.5-4% w/w. During combustion, the nitrogenous compounds of the wood are lost with the flue gas. Most other elements taken up as mineral nutrients by the tree during its growth, such as calcium, potassium and phosphorus, are retained in the ash (Table 1). Wood ash provides a source of base cations and other nutrients. Therefore, recycling of wood ash to forest soil has been suggested as a means to compensate for the nutrients removed. The dominant element in wood ash is calcium but the content of Si could also be high due to the presence of quartz sand, which is used as a bed material in the boilers.

Table 1. Major elements in wood fuel ashes from combustion units in Sweden and Finland, w/w % (Jönsson and Nilsson, 1996)

	Ca	Si	Al	K	Mg	Na	P	S
Median	17.0	7.6	1.4	4.2	1.9	0.7	0.9	0.5
Minimum	1.4	0.0	0.0	0.7	0.0	0.1	0.1	0
Maximum	54.9	31.0	6.8	15.0	6.7	3.6	2.7	6.5
No. ash samples	156	127	128	156	154	129	155	121

Wood ash has high contents of metal oxides, hydroxides and carbonates. Each of these elements dissolves at a different rate. The ash contains alkali metals such as K and Na, which are present in the form of salts. These salts are easily leached. Na and K occur also in silicates and feldspars. When loose ash is dissolved in water, the pH in the extract will be 11-13. Because the ash is highly alkaline, untreated ash can be troublesome to handle. In order to avoid the effects of a drastic increase in pH and salt concentration on the vegetation and in the soil, some type of pre-treatment of the ash is advisable. A pre-treatment includes mixing of the ash with water. Wood ash with a low content of unburnt matter reacts in a spontaneous "self hardening" of the ash (Steenari and Lindqvist, 1997). During the hardening process, also called stabilization, the particles form denser and larger aggregates. The self-hardening process takes some weeks, during which the moist ash is packed in a large pile and stored. Then the ash is crushed to a suitable fraction. This product is called crushed wood ash and is the ash type used in the present work. Alternatively, the ash can also be mixed with water and processed in a machine to pellets or granules, which are also considered to be slow-releasing forms of ash.

During hardening of the wood ash, there occurs a series of chemical processes some of them leading to the formation of secondary minerals with low solubility. The following important chemical reactions for Ca probably occur during the hardening process:

* hydroxide formation, e.g. $CaO + H_2O \rightarrow Ca(OH)_2$ (portlandite)

* carbonization of hydroxides, e.g. $Ca(OH)_2 + CO_2 \rightarrow CaCO_3$ (calcite)$+H_2O$

* formation of gypsum, $CaSO_4 + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O$

* formation of ettringite, $CaAl_2O_6 + 3CaSO_4 \cdot 2H_2O + 26H_2O \rightarrow$
$Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26H_2O$

Transformation of CaO over $Ca(OH)_2$ to $CaCO_3$ and the formation of ettringite lowers the Ca leaching rate. Portlandite is considered to be more soluble than calcite. Ettringite formation binds sulphur and aluminium and contributes to the stability of the ash structure. The carbonization process also contributes to a reduction in the alkalinity of the ash (Steenari and Lindqvist, 1997). The carbonization process of the ash continues in the field and probably dominates over Ca dissolution (Ohlsson, 2000). Alkali metals mainly occur as soluble salts and in silicate minerals with low solubility. Potassium and sodium and their counter anions chloride and sulphate are not incorporated into the solid phases during hardening. In a simulated laboratory test, Steenari et al. (1999) showed that the short-term release of these salts was not reduced by the hardening. Phosphorus, iron and magnesium have low leaching rates. Phosphorus is probably bound in apatite and other compounds with low solubility (Steenari and Lindqvist, 1997). Knowledge of the chemical composition and leaching rates of a particular type of wood ash is essential in the evaluation of this wood ash for recycling to forest soil.

Wood ash regulations and quality requirements

The National Board of Forestry has made recommendations for wood ash recirculation to forest soil (Anon., 2001b). The ash should originate from forest fuel, but some degree of mixing with other fuel ashes could also be possible. It is the quality of the ash that determine whether it is appropriate for use. The ash should be stabilized in order to accomplish slow release of plant nutrients. When whole-tree harvesting has been practised more than once during a rotation period, the forest owner should recycle wood ash. For areas with high acid and nitrogen depositions rates, the guidelines state that compensatory fertilization should always be carried out after harvesting of logging residues (Anon., 2001b). N-free mineral fertilizers could also be used for this purpose.

Wood ash used for recycling should meet certain requirements in terms of minimum and maximum concentrations of constituents (Table 2).

Table 2. Minimum or maximum content of elements in wood ash products for recycling to forest sites as recommended by the National Board of Forestry, w/w % or ppm (Anon., 2001b)

Ca %	K %	Mg %	P %	Cd ppm	Hg ppm	As ppm	Pb ppm
>12.5	>3	>2	>1	<30	<3	<30	<300

There are also recommendations on the maximum addition rate of certain elements during one forest generation. The basic idea is that no more than the amount of an element taken from a site at thinnings and at harvest should be put back within one forest generation. The major proportion of the heavy metals present in the biomass is retained in the ash fraction. There is a concern that heavy metal levels in the soil, particularly of Cd, would increase through short-term direct release from the added wood ash. Depending on where in Sweden wood ash is to be applied, the critical load limits differ for Cd. In southern Sweden (<60°N), a max. 100 g Cd ha^{-1} may be applied per forest generation with application of wood ash, while in central Sweden (60°-64°N) the max. is 50 g Cd ha^{-1} and in the north of Sweden (>64°N) the max. is 25 g Cd ha^{-1} (Anon., 2001b). Current research is trying to find new methods to separate Cd from the ash prior to application in the field (Sundqvist, 1999). The concern about direct leaching of Cd from the added ash could then be excluded.

Objectives

The overall aim of this thesis was to investigate the benefits and potential negative impacts of application of wood ash to young spruce stands. I examined the effects of crushed wood ash on ground vegetation, needle chemistry, soil and soil solution chemistry in young Norway spruce stands (*Picea abies* (L.) Karst.). A general hypothesis tested was that the effects of wood ash application would be dependent on the climatic situation as well as on site fertility.

More specific objectives were:

a) To determine the effects on the plant cover, species composition and above-ground biomass five years after application of crushed wood ash (Paper I).

b) To determine whether the nutrient levels in the foliage of young Norway spruce stands were influenced by application of crushed wood ash (Paper II).

c) To examine the chemical changes in the soil and soil solution after application of crushed wood ash (Papers III and IV).

The ash dose applied, 3000 kg ha^{-1}, is the application rate recommended by the National Board of Forestry in Sweden in order to compensate for base cation losses at whole-tree (above-ground) harvesting (Anon., 2001b).

Materials and methods

Site descriptions

The sites included in the studies were situated in four climate zones. In each climate zone, three sites representing a site fertility gradient were included (Fig.1).

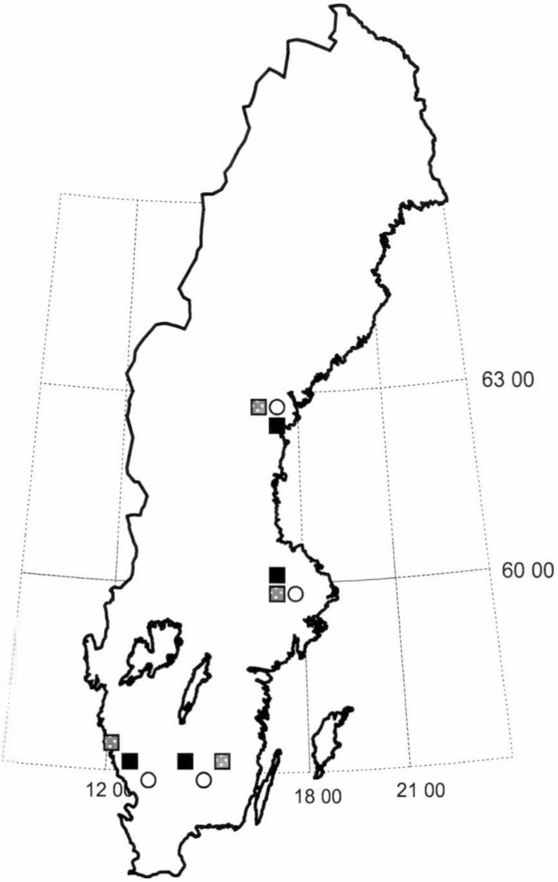

Figure 1. Location of the twelve sites included in the studies. Symbols: ■ sites with forest type *Vaccinium*, ○ sites with forest type grass, □ sites with forest type herb. Four generalized climatic zones as they can be found in the National Atlas of Sweden (Anon., 1990) are used; the South West (SW), the Southern Highlands (SH), the south East (E) and the Northern Coastal area (N). Map by Johan Stendahl, SLU.

The field sites used for the investigations presented here chosen to represent different climatic conditions and the following four generalized climatic zones as they can be found in the National Atlas of Sweden (Anon., 1990): The South West (SW) and the Southern Highlands (SH) with high and fairly high acidifying deposition, respectively; the south East (E) with less acidifying deposition; and the Northern Coastal area (N) where the deposition is low (Table 3). The Northern

Coastal area has dry summers and a slightly humid climate in a broad belt along the coast of Norrland. The South East has a favourable temperature climate but dry summers and is less humid. The South West has high precipitation and a markedly humid climate and the Southern Highlands area has a humid climate.

Table 3. Sites included in the thesis. The sites are abbreviated according to the climate zone and forest type. Climate zones are South West (SW), Southern Highlands (SH), south East (E) and Northern coastal area (N). The forest types are *Vaccinium myrtillus*, grass and herb vegetation. All sites were whole-tree harvested. Harvesting was carried out between 1988-1991, except at site N:*Vacc.* (1987). All sites were replanted with Norway spruce

Abbrev. climate zone: forest type	Site name	Latitude longitude	Wet deposition of nitrogen (kg ha^{-1} year^{-1})	Precip. (mm year^{-1})	Paper
SW:*Vacc.*	Flybacken	56° 45'N 13° 23'E	12-14	800	I, II, III, IV
SW:grass	Tönnersjö	56° 40'N 13° 05'E	12-14	800	II, IV
SW:herb	Kvibille	56° 47'N 12° 50'E	12-14	800	II, IV
SH:*Vacc.*	Ljungby	56° 50'N 14° 00'E	10-12	650	I, II, III, IV
SH:grass	Sjöamellan	56° 48'N 14° 54'E	10-12	650	II, IV
SH:herb	Birsasjön	56° 58'N 14° 59'E	10-12	650	II, IV
E:*Vacc.*	Simtuna	59° 42'N 16° 50'E	6-8	540	I, II, III, IV
E:grass	Vidingsbo	59° 38'N 17° 11'E	6-8	540	I, II, IV
E:herb	Teda	59° 33'N 16° 56'E	6-8	540	I, II, IV
N:*Vacc.*	Malungsfluggen	62° 10'N 16° 53'E	2-4	570	I, II, III, IV
N:grass	HuljenA	62° 26'N 17° 54'E	2-4	570	II, IV
N:herb	HuljenB	62° 26'N 17° 54'E	2-4	570	II, IV

In each climate zone, the thesis also included a site fertility gradient represented by sites of three different forest types; *Vaccinium myrtillus*, grass and herb vegetation according to Hägglund and Lundmark (1977). The species composition of the ground vegetation has been shown to be correlated to the soil fertility, a factor which has traditionally been used in the Nordic countries as a forest site classification system (Cajander, 1926; Eneroth, 1936; Arnborg, 1964; Hägglund and Lundmark, 1977). Each site is assigned to a forest type named after the plant community in the mature forest. The sites in the thesis are classified in the order of increasing fertility: *Vaccinium myrtillus*, grass and herbaceous forest types.

In the papers, the sites are abbreviated according to the climate zone and forest type: SW:*Vacc.*, SW:grass, SW:herb; SH:*Vacc.*, SH:grass, SH:herb; E:*Vacc.*, E:grass, E:herb; N:*Vacc.*, N:grass, N:herb or according to their site names (Table 3). The spruce stands differed in age and were 1-4 years old when the wood ash was applied in 1993. All sites had been whole-tree harvested and planted with Norway spruce (*Picea abies* (L.) Karst).

Experimental design and treatments

The experiments had a randomized block design, with three treatments and four blocks at each site (one replicate per block, n=4), i.e. 12 plots per site. Each 3 m × 3 m plot was surrounded by a 0.5 m border strip. Within a plot there were four planted Norway spruce trees. The treatments were control, application of wood ash Nymölla (WAN) and application of wood ash Perstorp (WAP). The ashes were from district heating plants. Wood ash Nymölla originated from a cyclone furnace fired mainly with bark, whereas wood ash Perstorp originated from a circulating fluidized bed boiler fired with 90% wood chips and 10% peat. After combustion, the ashes were stabilized by addition of water and allowed to harden before being crushed. The chemical composition as determined by a $LiBO_2$ melting technique differed between the ashes (Table 4).

Table 4. Chemical composition (%) of the wood ash Nymölla (WAN) and the wood ash Perstorp (WAP). LOI=loss-on-ignition

	Ca	Si	Al	K	Mg	Na	P	S	LOI	Cd (ppm)
WAN	29.7	9.5	3.2	1.0	2.4	0.6	0.4	1.4	19.4	5.4
WAP	16.2	10.7	4.9	2.0	2.0	1.6	0.4	2.9	13.8	10.4

A single dose of 3000 kg ha^{-1} (dry mass) of crushed wood ash was applied by hand as uniformly as possible to each ash treated plot in August to October, 1993. The dose applied is what is recommended by the National Board of Forestry in order to compensate for base cation losses at whole-tree (above-ground) harvesting (Anon., 1998).

Ground vegetation (Paper I)

The vegetation study included the *V. myrtillus* sites over the whole climatic gradient and the three sites of the fertility gradient in climate zone south East (Table 3).

The vegetation observations were made between mid-June and mid-July in 1998. In 0.25-m^2 quadrants, the cover of vascular plants and bryophytes was estimated visually according to a percentage scale (<1, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 25, 30, 40 ....100%). Vascular plants were determined to species. Lichens and mosses were treated more generally and determined to genus with the exception of some easily identified and abundant species. The biomass samples were sorted into five fractions; herbs, graminoids, shrubs, bryophytes and lichens.

Needle chemistry (Paper II)

The needle chemistry study used all sites in the climate and fertility gradients (Table 3).

Current-year needles (C) and previous year needles (C+1) were sampled once a year from 1993 to 1998, i.e. once before and five times after ash application. The samplings were carried out between October and December. The needles were analyzed for total nitrogen, P, K, Ca, Mg, S and Cd. Nutrient conditions in the needles were expressed both as concentration per unit dry weight and element:nitrogen ratios (% weight basis). Element:nitrogen ratios were used because they reduce the variation caused by seasonal changes in needle carbohydrate contents (Linder, 1995).

Soil chemistry (Paper III)

The soil chemistry study included the *V. myrtillus* sites over the whole climatic gradient (Table 3).

The following soil chemistry parameters were analyzed six years after application of crushed hardened wood ash: exchangeable Ca, Mg, K, Na and Cd, cation exchange capacity (CEC_{eff}), pH, electrical conductivity, exchangeable acidity, base saturation, extractable NH_4^+, NO_3^- and total C and N. The soil was divided into layers 0-5, 5-10 and 10-20 cm below the soil surface. The 0-5 cm layer consisted of a mixture of humus and mineral soil materials because of soil scarification.

Soil water chemistry (Paper IV)

The soil water chemistry study used all sites in the climate and fertility gradients (Table 3).

The concentrations of NO_3-N, Ca, Mg, K, Na, Al and pH in the soil solution at 50 cm depth in the soil were analyzed three or four times every year for six years after wood ash application.

Statistical analyses

In general, for analysis of treatment effects on investigated variables within sites, an analysis of variance (ANOVA) for randomized block design and significance tests was carried out using the programme Super-Anova Abacus Concepts., Inc. Least significant difference tests used the Tukey-Kramer test to detect differences between treatment means at the $p<0.05$ level. In Paper I, analysis of mean percentage cover for each species and plot was made after log transformation of the data in order to improve normality and to obtain approximately homogeneous variances. In Papers II and III, no transformation of data was considered necessary, since the variances were fairly homogeneous.

In Papers I and III, a nested model was used to examine general treatment effects across all sites with the *Vaccinium myrtillus* forest type. In addition, a nested model was used in Paper I to examine general treatment effects across all sites with different forest types in climate zone south East. In the nested model sites, treatments and blocks (blocks nested within sites), including the interaction between sites and treatments, were used as sources of variation.

In Paper II, a nested three factorial (treatment, forest type and climate zone) ANOVA was used to examine general treatment effects across climate zones and forest types. Differences in treatment effects between climate zones and forest types can be detected from the interaction term. Blocks nested within climate and forest type were used as sources of variation for climate zone and forest type. Treatment, interaction between treatment and climate zone and interaction between treatment and forest type used mean square of error as the source of variation.

In Paper IV, the soil solution concentration data were analyzed according to a mixed linear model. In order to account for repeated measurements, a first order autoregressive covariance structure on residuals was used. For each tested variable, yearly mean values were used in the model.

A four factorial model was used to examine general treatment effects across climate zones, forest types and years. Four blocks for each combination of forest type and climate zone were used. Hence, treatment, interaction between treatment and climate zone and interaction between treatment and forest type used block× treatment nested within climate and forest type as error term. The interaction between treatment and year; the interaction between treatment, climate zone and year; the interaction between treatment, forest type and year all used mean square of error as error term.

Results and discussion

Ground vegetation

An important result was that almost no decreases and only a few increases in the cover of different vascular plant species were found five years after application of hardened and crushed wood ash in a compensatory dose of 3000 kg ha^{-1}.

The bryophytes were unaffected five years after application. Bryophytes are susceptible to the high ion concentrations that may have occurred in connection with application. It is possible that the bryophytes suffered immediate damage, but soon recovered to the level of the control plots. In another experimental study, Kellner and Weibull (1998) found that there was short-term initial damage three months after application of wood ash Perstorp (WAP) but that the bryophytes recovered gradually during the three year study period. The degree of the damage depended on the ash dose, with the highest degree of damage caused by 8000 kg ha^{-1} crushed ash and lowest damage caused by 2000 kg ha^{-1}. After three years there was no visible damage.

At sites with forest type *Vaccinium myrtillus,* the cover of *Calluna vulgaris* was generally lower in WAP-treated plots than in the control and wood ash Nymölla (WAN) treated plots (Fig. 2). Compared with control plots, the total cover of *C. vulgaris* decreased by 7%-units in WAP-treated plots. Like *Vaccinium myrtillus* and *V. vitis-idaea*, *C. vulgaris* might be sensitive to high salt concentrations near the root (Ingestad, 1973; 1974). Nohrstedt (1994) showed reduced cover of *V. myrtillus* after repeated addition of PK-fertilizers. He hypothesized that the accompanying ions, e.g. chloride or sulphate, occur in concentrations that would be toxic to the plants. This was also indicated by Mälkönen et al. (1980). Steenari et al. (1998) showed high losses of cations from WAP compared to WAN after weathering in a forest soil for 1.5-2.5 years. WAP had a higher S, K and Na contents than WAN, which indicates that it had a higher content of easily dissolved sulphates and other neutral salts, and in fact WAP gave a higher electrical conductivity in a shake test than other crushed hardened ashes (Eriksson et al., 1998). Another explanation could be that there was a change in competition between species due to the ash application. Studies of forest fertilization have shown an increased competition from grasses at the expense of dwarf shrubs (Hester et al., 1991; Kellner, 1993). However, the decrease in cover of *C. vulgaris* was not accompanied by an equal increase in *Deschampsia flexuosa* or other grasses in WAP-treated plots in our investigation.

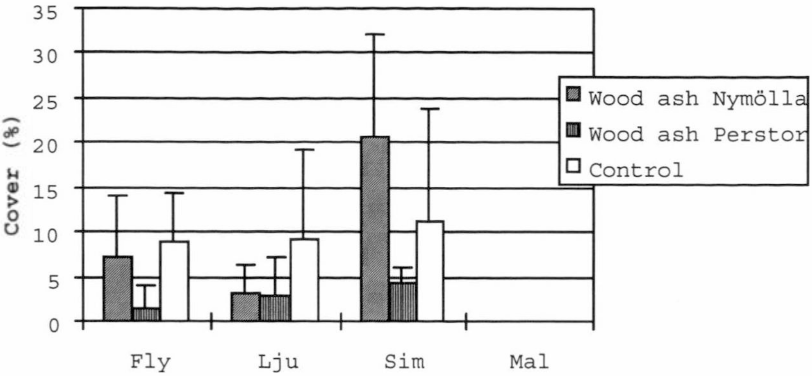

Figure 2. Mean cover of *Calluna vulgaris* at four study sites Fly=Flybacken, Lju=Ljungby, Sim=Simtuna, Mal=Malungsfluggen. Mean values and SD are shown for each treatment, n=4.

There was a tendency for increased cover of *Deschampsia flexuosa* in both WAP and WAN-treated plots compared to control plots (Fig. 3). On average *D. flexuosa* increased by 1%-unit in ash treated plots compared to control plots. Liming of forest soils seems to increase the cover of *D. flexuosa* in general (Hallbäcken and Zhang, 1998). The increase in cover of *D. flexuosa* in our study indicated that a change in nitrogen availability might have occurred. Liming may increase nitrogen availability through increased mineralization when the C/N ratio is below 30 (Persson and Wirén, 1995). However, there was no difference in the humus C/N ratio between the ash treatments three years before the ground vegetation was studied.

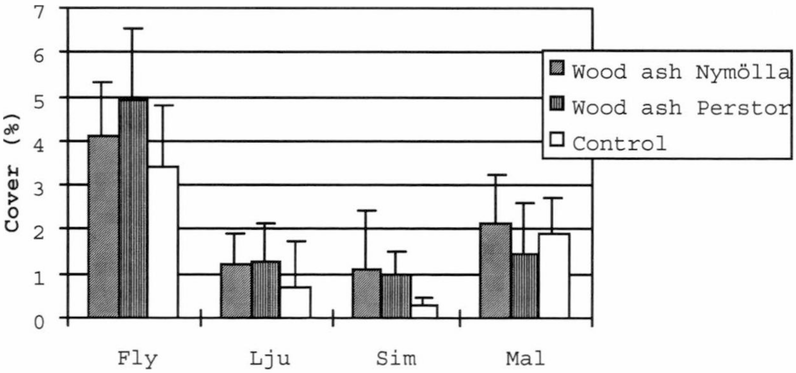

Figure 3. Mean cover of *Deschampsia flexuosa* at four study sites Fly=Flybacken, Lju=Ljungby, Sim=Simtuna, Mal=Malungsfluggen. Mean values and SD are shown for each treatment, n=4.

None of the ash types affected the species composition of the plant community at sites with the *V. myrtillus* or herb forest type. However, the site with the grass forest type possibly developed a similarity with herb sites after application of WAN. On this site there was a tendency for higher mean number of species in WAN-treated plots compared to control plots. Three species, *Epilobium angustifolium*, *Fragaria vesca* and *Cirsium* spp. occurred in WAN-treated plots only and not in the other treatments. However, the cover of these species was <0.1%. On the other sites, the ash treatments did not affect the plant community composition. This indicated that wood ash application may have improved site fertility. However, since this tendency was limited to one ash type it also indicated that the chemical composition of the hardened crushed wood ash seemed to be of importance for the vegetation changes, even when the dose of ash applied was low. The biomass of different field vegetation components was not affected by the ash application.

Needle chemistry

The results from the study on effects of wood ash on needle chemistry showed that application of hardened wood ash increased the concentrations of the nutrients P, K and Ca in current and one-year-old needles after a period of five years. The results were consistent over all stands, irrespective of climate zone or site fertility (Table 5). A treatment effect was also noted in terms of increased ratios of P:N, K:N and Ca:N in one-year-old needles. The needle concentrations of Mg and S were not affected by the ash applications. Wood ash seems to be a good measure to counteract the losses of Ca, Mg and K and to improve the Ca and K status of the trees. However, I was unable to directly compare the amounts of nutrients removed at harvest of the felling residues with the amounts added with ash in my study.

The P and K concentrations were higher in spruce needles from plots treated with WAP, whereas Ca concentrations were higher in those of WAN-treated plots (Paper II). WAN-treated plots showed lower exchangeable acidity (exchangeable Al and exchangeable H) compared to WAP-treated plots (Paper III). A negative impact of Al on the uptake of Ca has been observed (Asp et al., 1988; Bengtsson et al., 1988; Gobran et al., 1993; Ericsson et al., 1995). Al probably competed with Ca on the root surface and limited the uptake of Ca in WAP-treated plots.

The treatment effect that P concentration increased in both current and one-year-old needles in plots treated with wood ash Perstorp (WAP) compared with control plots is somewhat surprising, since a previous study by Clarholm and Rosengren-Brinck (1995) using granulated wood ash showed different results. They found no effect on needle concentration of P or on the P:N ratio one to four years after application of granulated wood ash at a dose of 3200 kg ha^{-1} in a field trial with spruce in southwest Sweden. In the same field trial after five years, a bioassay for ^{32}P uptake rates indicated P deficiency (Clarholm, 1998). However, since the microbial biomass was significantly higher in wood-ash treated plots compared to control plots, Clarholm (1998) suggested that increased P availability may follow if there is a net decrease in microorganisms.

Table 5. Analysis of variance (ANOVA) of needle concentrations five years after wood ash application. The F-ratios for different factors and interactions are given

Dependent variables	Treatm. (2 df)	Treatm. × Climate zone (6 df)	Treatm. × Forest type (4 df)
Nutrient conc. in current needles (C)			
N	0.69	0.60	1.13
P	42.8***	3.04*	1.02
K	9.87***	0.38	0.05
Ca	19.2***	2.03	0.60
Mg	3.25*	1.86	0.95
S	1.80	1.37	0.78
Cd	6.81**	1.21	1.20
Nutrient conc. in one-year-old needles (C+1)			
N	0.78	1.23	0.58
P	51.4***	1.74	0.91
K	19.1***	1.02	0.20
Ca	18.5***	2.03	1.28
Mg	1.54	0.46	2.00
S	2.89	1.35	1.05
Cd	5.32**	1.42	1.68
Nutrient ratio in one-year-old needles (C+1)			
P:N	34.7***	1.30	1.29
K:N	14.5***	1.64	0.35
Ca:N	19.2***	1.12	0.70
Mg:N	0.98	0.95	1.50

* $p<0.05$, ** $p<0.01$, *** $p<0.001$

The ashes used in the study, WAN and WAP, both contained 0.4% of P. In samples from the field, P losses of 20% were found in the WAP (called CFB B ash) and only a few percent in WAN (called CF ash) by Steenari et al. (1998). Even though the chemical solubility of ash is low for P, it can still be plant available. Granulated wood ash has been shown to be colonized by ectomycorrhizal mycelia (Mahmood, 2000). P compounds identified in wood ash, mainly hydroxyl apatite, have low solubility. Studies have shown that pine seedlings with ectomycorrhizal fungi grown with apatite as their P source grew significantly better and had higher P concentrations than seedlings grown without any P source, indicating that they were able to use apatite-P (Wallander et al., 1997; Wallander, 2000). The mycorrhizal mycelia colonizing the ash particles may be involved in direct uptake of P.

Analyses across all study sites showed a treatment effect on cadmium concentration in the needles (Table 5). There was a tendency for decreased Cd concentration in the needles in the WAN treatment. Column leaching tests of WAP have shown a slight increase in Cd in the leachates (J. Eriksson, 1998). This effect was stronger in the presence of a mor layer than in a sand layer, from which fact it was concluded that Cd was not leached from the ashes, but mobilized from the exchangeable fraction of Cd in the humus. In the upper 5 cm of the soil, WAN application increased soil pH on average by 0.7 pH units compared to pH in the control plots (Paper III). The pH level influences the solubility of soil Cd. Plant available Cd decreases with increasing pH, which could explain the lower concentrations of Cd in WAN-treated plots.

Soil chemistry

Exchangeable Ca, Mg, K and effective cation exchange capacity (CEC_{eff}) on a per hectare basis in the 0-20 cm soil layers were significantly higher in wood ash treated plots than in the control plots in analyses across all study sites with the forest type *Vaccinium myrtillus* (Table 6).

Table 6. General treatment effect on pools of exchangeable Ca, Mg, K, Na, effective cation exchange capacity (CEC_{eff}) and total acidity ($kmol_c\ ha^{-1}$) in the 0-20 cm soil layer. *p*-values are shown when $p<0.05$ for treatment, site and the interaction between site and treatment

Dependent variable	Treatment (2 df)	Site (3 df)	Treatment× site (6 df)
Ca	0.0001	ns	ns
Mg	0.0018	ns	ns
K	0.0268	0.0001	0.049
Na	ns	0.0003	0.0437
CEC_{eff}	0.02	0.0078	ns
Tot. acidity	0.0002	ns	ns

Application of WAN and WAP gave positive effects in terms of increased pools of Ca in our study. According to the results, the pools of exchangeable Ca were on average 16 and 11 $kmol_c\ ha^{-1}$ higher after WAN and WAP addition, respectively, compared to the control (Fig. 4A). The concern about whole-tree harvesting has been about nutrient removal and how to sustain long-term nutrient budgets. At four whole-tree harvested sites that were investigated 15 years after clearfelling, Olsson et al. (1996) found that the soil pools of

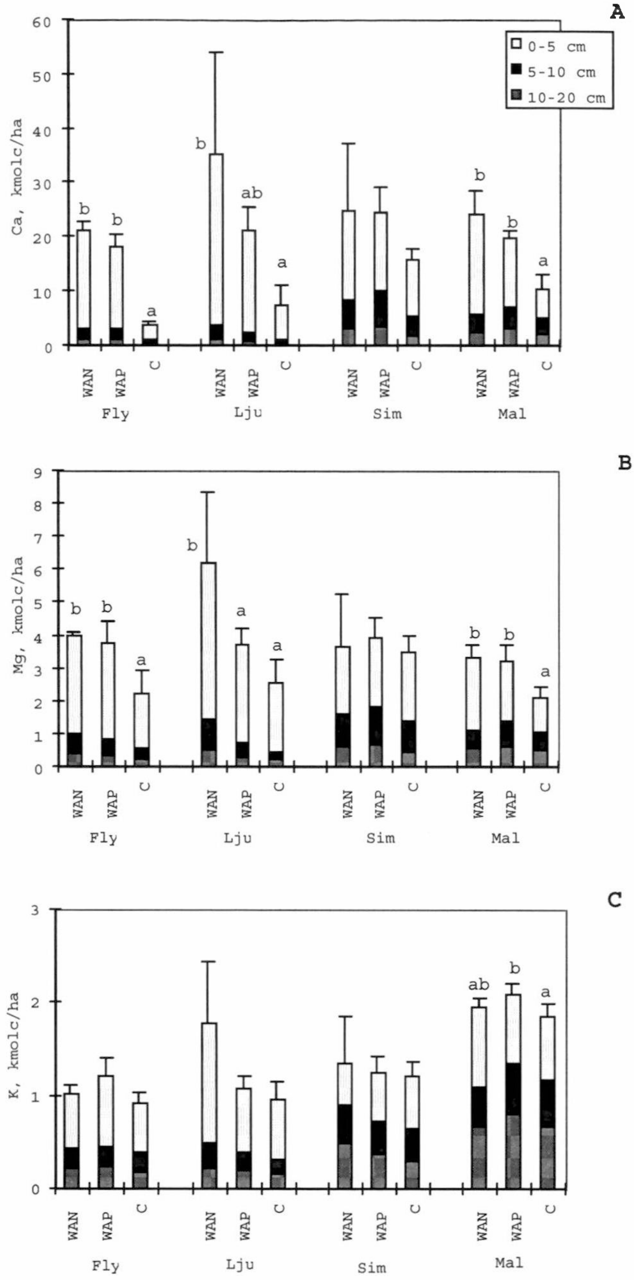

Figure 4. Amounts of exchangeable Ca (A), Mg (B) and K (C) in the soil after wood ash application ($\text{kmol}_c\ \text{ha}^{-1}$). Mean values for each site and treatment are given. Each bar is subdivided into 0-5, 5-10 and 10-20 cm layers of the soil from top to bottom. The treatments (*n*=4) were: WAN=wood ash Nymölla, WAP=wood ash Perstorp, C=control. SD bars refer to the total amounts. Bars with the same or no letter are not significantly different ($p<0.05$) according to the Tukey-Kramer test.

exchangeable Ca were 0-6 $\mathrm{kmol_c\ ha^{-1}}$ lower in whole-tree harvested plots compared to those in conventionally harvested plots. Thus, the wood ash dose used in our study increased the pool of exchangeable Ca more in absolute terms than it was reduced by whole-tree harvesting in the study by Olsson et al. (1996).

The Mg pool increased by approximately 1-3 $\mathrm{kmol_c\ ha^{-1}}$ after wood ash addition (Fig. 4B). With WAN and WAP, we applied 6 and 5 $\mathrm{kmol_c\ ha^{-1}}$ Mg respectively. Steenari et al. (1998) reported losses of Mg between 10-30% after a weathering time of 2.5 years. Similar results were found in a column leaching test simulating a weathering period of five years (J. Eriksson, 1998). Mg has been observed as MgO and Mg silicates in ashes (Steenari and Lindqvist, 1997). The low chemical solubility of Mg was probably due to the high pH. Steenari et al. (1998) noticed a slight increase in leaching of Mg towards the end of a simulated leaching period. The low recovery of Mg in our study suggests that more Mg will be leached from the ashes with time.

The exchangeable concentrations and the exchangeable pool of K were hardly affected by wood ash application in our study (Fig. 4C). Two years after application of an untreated wood ash in a high dose of 20 tonnes $\mathrm{ha^{-1}}$, Kahl et al. (1996) found increased potassium concentrations in the mineral soil. Unger and Fernandez (1990) noticed an increase in K in the mineral soil with doses ranging from 4 to 20 tonnes $\mathrm{ha^{-1}}$ of untreated wood ash. From a laboratory study using WAP, J. Eriksson (1998) reported that approx. 50% of the original K was lost in a column leaching test, corresponding to approx. 5 years weathering in the field. A similar release was found in samples collected from the field after 2.5 years of weathering in the forest (Steenari et al. 1998). Since exchange sites on the soil particles attract Ca more strongly than they attract K, the low recovery of K on the exchange site could be due to greater leaching of K, but probably also to higher uptake by trees. In analyses of one-year-old needles, I found that five years after ash application, K concentration and the K:N ratio were in general higher in wood ash treated plots compared with a control (Paper II). Furthermore, consecutive suction lysimeter samplings of the soil water at 50 cm depth for six years after wood ash application indicated higher concentrations of K in the soil water from ash treated plots compared to control plots (Paper IV).

In the upper 5 cm of the soil, hardened wood ash application increased the pH by 0.7 pH units in WAN-treated plots and 0.5 pH units in WAP-treated plots compared to control plots. The effects on soil pH were less than after application of loose wood ash in similar doses, but higher than after application of granulated wood ash (Kahl et al. 1996; Eriksson, 1998; Levula et al., 2000). The concern about effects of high pH is that it might lead to damage to the vegetation and/or soil fauna. However, I found no effects on the cover of different bryophyte species five years after ash application of WAP and WAN (Paper I).

Soil water chemistry

The overall results from the study on effects of wood ash on soil solution chemistry did not show any increased concentration of NO_3-N in the soil water at 50 cm depth. Furthermore, the wood ash addition did not affect the soil water pH or the concentration of Na and Al (Table 7). However the concentrations of Ca, Mg and K in the soil water were higher in wood ash treated than in control plots. These results were consistent over all sites.

Table 7. General treatment effect on pH and the concentration of NO_3-N, Ca, Mg, K, Na and Al in the soil water at 50 cm depth. *p*-values from the analysis of variance according to the mixed linear model. Treatm.=Treatment, Clim.=Climate zone, For. type= Forest type

Variable	Treatm.	Treatm. × Clim.	Treatm. × For. type	Treatm. × Year	Treatm. × Year × Clim.	Treatm. × Year × For. type
NO_3^--N	ns	ns	0.0042	ns	ns	0.0165
pH	ns	ns	ns	ns	ns	ns
Ca	0.0001	0.02	ns	0.0001	0.0125	ns
Mg	0.0001	0.0367	ns	0.0001	0.0001	ns
K	0.042	ns	0.0498	0.003	ns	ns
Na	ns	ns	ns	0.0001	ns	ns
Al	ns	ns	ns	ns	ns	ns

When wood ash is applied immediately or soon after clearfelling, it is assumed to aggravate and increase the risk of losses of NO_3-N and cations in the soil water below the rooting zone. Addition of wood ash may contribute to a higher pH in the soil and thereby to increased nitrification (Meiwes, 1995; Kahl et al., 1996). Increased leaching of nitrate in the soil water has been shown after application of high doses (4-8.75 tonnes ha^{-1}) of lime (Marschner et al., 1992; Kreutzer, 1995; Nilsson et al., 2001). However, liming with a small dose (1 ton ha^{-1}) did not show any leaching of NO_3-N (Nohrstedt, 1992).

There were no overall treatment effects on NO_3-N in the soil water. At seven sites we found no NO_3-N in the soil water. We found elevated concentrations of nitrate at five sites. (Fig. 5). At site SH:*Vacc.* two and three years after ash addition, the concentration of NO_3-N was higher in WAN-treated plots compared to control plots. Also at site N:herb, five years after ash addition, there was a two fold higher concentration of NO_3-N in WAN-treated plots compared to control plots (Fig. 5). Soil pH and ammonium availability are two factors that influence nitrification. Rudebeck and Persson (1998) have shown that inactive populations of nitrifiers can respond to increased pH levels in the soil after several years. Accordingly, this may indicate a risk for increased leaching of nitrate several years after wood ash application. At sites with the *Vaccinium myrtillus* forest type in the upper 5 cm of the soil, pH increased by 0.5 pH units in WAP-treated plots and by 0.7 pH units in WAN-treated plots compared to control plots (Paper III).

Despite these quite substantial increases in soil pH, we found no overall increase in NO_3-N in the soil solution during the six years of sampling.

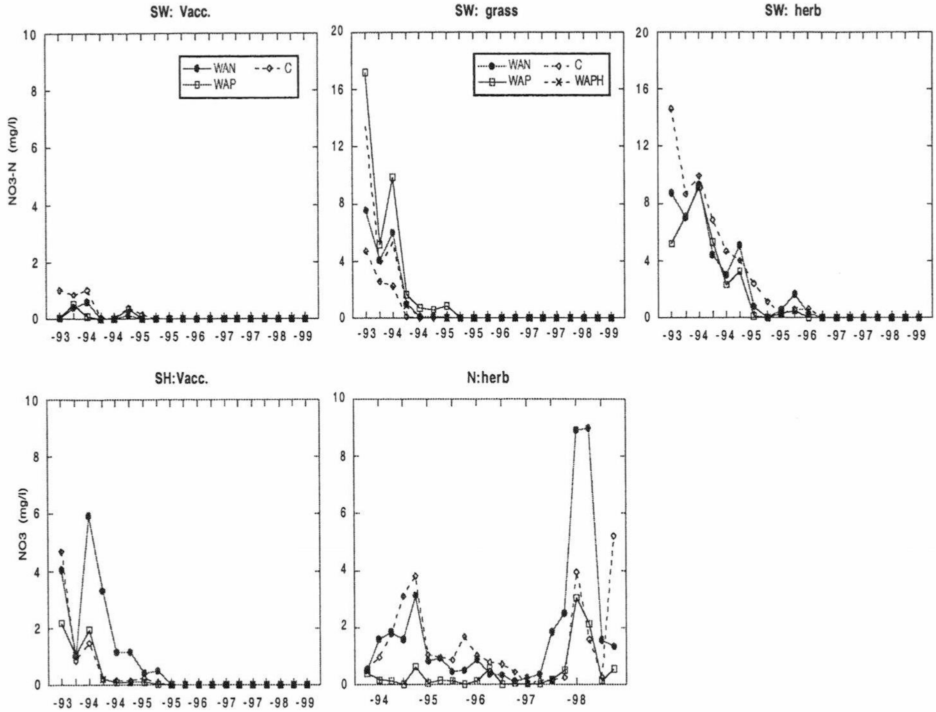

Figure 5. Concentration (mg/l) of NO_3-N in soil water at 50 cm depth below the soil surface. The wood ash was applied after the first sampling occasion. The treatments were WAN= wood ash Nymölla, WAP=wood ash Perstorp, C=control

The initially high concentrations of NO_3-N in both treated and control plots on sites SW:grass, SW:herb and SH:*Vacc.* probably resulted from nitrification caused by soil disturbance. Johnson et al. (1991) found peak concentrations of NO_3-N in the soil water due to soil disturbance following lysimeter installation. Nitrate could be monitored as an indicator of disturbance effects resulting from the installation procedure (Kahl et al., 1996). This demonstrates that installation of the ceramic cups in our experiments should be done some time before the start of the treatment. Six months or more have been recommended to allow tension lysimeters to be in equilibrium with the surrounding soil (Litaor, 1988).

The concentrations of Ca, Mg and K in the soil water were higher in wood ash treated plots compared to control plots (Table 7). These results were consistent over all sites. However, there was a significant interaction between treatment and climate zone for Ca and Mg, suggesting that the treatment effect varied with climate zone. Increased leaching of Ca and Mg has also been shown five years after application of granulated wood ash at a dose of 3200 kg ha^{-1} to a 30 year old Norway spruce stand in southern Sweden (Lundell et al., 2001). The concentrations of Ca and Mg in WAP-treated plots in climate zone N were elevated for a longer period of time than in the other climate zones. A rapid increase in Ca and Mg concentrations following addition of wood ash was shown in all climate zones except zone N. Thus, it is likely that nutrient release from the ashes and subsequent leaching was lower in the Northern coastal area than in the South. In general, a faster treatment effect but of shorter duration could be expected to occur in the South, owing to higher precipitation.

Addition of wood ash caused an immediate increase in Ca concentration. The Ca concentration gradually decreased during the five years after ash addition and after six years the concentration was at the same level as in control plots. A significant interaction with treatment, climate and year suggests that the treatment effect varied with year (Table 7). Results from modelling of the solid phase in wood ash particles suggest that after a weathering time of two years, Ca in the ash is present in the form of calcite ($CaCO_3$) and the release rate is slowed down (Steenari et al., 1998). Furthermore, a laboratory leaching test showed that the leaching of Ca decreased with time (Steenari et al., 1998). This was explained as being caused either by calcium depletion of ash particle surfaces or by inhibition of dissolution by a new phase precipitating on the particle surface.

In general, the effects of wood ash application seem to be consistent over all sites, irrespective of climatic conditions. However, the treatment effect of wood ash application on the concentration of soil water Ca and Mg appeared to be an exception. The fertility of a site, in this thesis represented by sites classified according to the species composition of the ground vegetation, had no influence on the effect of wood ash application.

Conclusions

The main objective of this thesis was to investigate the benefits and possible negative impacts of application of crushed wood ash in a compensatory dose to young spruce stands that had been intensively harvested. At the preceding harvest, logging residues were removed from the sites (whole-tree harvesting).

The effects of wood ash application on the ground vegetation composition or cover were limited. Wood ash application generally resulted in significantly increased concentrations of exchangeable Ca and Mg in the soil and increased concentrations of P, K and Ca in the needles. Wood ash seems to be an appropriate measure to counteract the losses of Ca and Mg after whole-tree harvesting and to improve the Ca and K status of the trees. However, since the experimental sites had no control plots on which logging residues were left I could not directly compare the amounts of nutrients removed at harvest of the felling residues with the amounts added with ash in my study.

No increase in NO_3-N concentration in the soil water at 50 cm depth in the soil was found after addition of crushed wood ash to spruce stands shortly after clearfelling. This is an important aspect for the ability to apply wood ash without causing any damage to the environment.

In general, the effects of wood ash application appeared to be consistent over all sites, irrespective of climatic conditions or site fertility factors. The fertility of a site was classified according to the species composition of the ground vegetation.

In conclusion, crushed wood ash could be applied at a compensatory dose of 3000 kg ha^{-1} to young spruce stands without any detrimental effects on forest plants or increased concentrations of nitrate in the soil water below the rooting zone. Wood ash application would most likely compensate for nutrients removed at intensive harvesting and improve the P, Ca and K status of the trees. This is an important message to forest managers aiming to maintain long-term forest production under sustainable nutrient conditions, even with intensive forest management practices such as whole-tree (above-ground) harvesting.

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