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Effects of wood ash, green residues and N-free fertiliser on naturally regenerated birch and field vegetation in a young Norway spruce stand in SW Sweden

Per-Olov Brandtberg[a], Pei Wang[a], Bengt A. Olsson[a], Helen Arvidsson[a,b] and Helene Lundkvist[a]

[a]Department of Ecology, Swedish University of Agricultural Sciences, Uppsala, Sweden; [b]Department of Urban and Rural Development, Swedish University of Agricultural Sciences, Uppsala, Sweden

ABSTRACT

Treatments added to young conifer stands aiming to compensate for the loss of nutrients and alkalinity associated with whole-tree harvesting for bioenergy purposes have the potential to affect the growth of competitors to the conifers. Three different nutrient compensation treatments were applied to a young *Picea abies* (L.) Karst. stand in south-west Sweden, 2 or 3 years following final felling. The treatments were; fine fraction of harvest residues (15 Mg dw ha^{-1}); granulated wood ash (4.1 Mg dw ha^{-1}); nitrogen-free vitality fertiliser (twice 1.5 Mg ha^{-1}); untreated control. Root biomass and total biomass of graminoids (mainly *Deschampsia flexuosa* (L.) Trin) were significantly greater in the wood ash and vitality fertiliser treatments than in the residues and control treatments. The aboveground and coarse root biomass of naturally regenerated birch (*Betula* spp.) and the aboveground biomass of dwarf shrubs (mainly C*alluna vulgaris* (L.) Hull.) and bottom layer were not affected by the treatments. Calcium and magnesium concentrations in the aboveground biomass of graminoids and phosphorus concentration in the biomass of bottom layer were significantly the highest in the vitality fertiliser treatment. Thus, nutrient compensation with vitality fertiliser or granulated wood ash may increase competition from graminoids in the establishment phase.

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Wood ash; Norway spruce; birch; *Betula spp.*; *Deschampsia flexuosa*; competition

Introduction

There is growing demand worldwide for renewable energy sources that can replace fossil fuels. In Sweden and some other European countries, biofuels originating from forests comprise an important share of renewables (Forsum et al. 2018; Verkerk et al. 2019). In the future expansion of biofuel use in Sweden, the largest potential source is logging residues from tree felling (Börjesson et al. 1997; Lundmark et al. 2015). However, the exploitation of this source could have consequences for the environmental quality and long-term sustainability of forest sites (Weetman and Webber 1972; Kimmins 1976; Mälkönen 1976; Rothpfeffer and Karltun 2007; De Jong et al. 2017; Akselsson and Belyazid 2018). Since the harvesting of logging residues is associated with the increased export of nutrients and alkalinity from forest sites (Akselsson and Belyazid 2018), different ways to compensate for this loss have been discussed and tested. In south-west Sweden, where atmospheric deposition of nitrogen (N) is relatively high, and on N-rich sites elsewhere, N-free amendments such as wood ash (Andersson and Lundkvist 1989; Akselsson 2005; Levin and Eriksson 2010) or commercial N-free fertilisers may have benefits. Wood ash is of particular interest in Sweden, which aims to increase the use of wood ash as a source of nutrients and alkalinity to forest sites subjected to whole-tree harvesting (Swedish Forest Agency 2019). This is also the case in, e.g. Finland and Canada, where biomass represents an increasing proportion of renewable energy (Huotari et al. 2015; Hannam et al. 2018). The area subjected to wood ash recycling in Sweden is currently approximately 10,000 ha (mainly in southern Sweden), whereas the area subjected to whole-tree harvesting is eight-fold higher, indicating great potential for the increased use of wood ash (Swedish Forest Agency 2019). Where wood ash recycling is not feasible, an alternative is to separate the green needles from branches at the forest site prior to the extraction of branches (Swedish Forest Agency 2019). This reduces exports of nutrients and alkalinity, since needles are especially rich in nitrogen (N), phosphorous (P) and base cations (Olsson and Westling 2006).

The effect of compensatory amendments on conifer growth is an important factor for the willingness of forest managers to invest in post-harvesting treatments. It is generally believed that wood ash-based amendments give a positive growth response in conifers growing on sites, where the humus carbon-to-nitrogen ratio (C/N) is less than approximately 30, and a negative growth response on poor sites with C/N above this value (Swedish Forestry Agency 2019). This is based on observations in a series of experiments with wood ash amendment in 25- to 60-year-old conifer stands in Sweden (Jacobson et al. 2014). However, if wood ash is to

CONTACT Bengt A. Olsson bengt.olsson@slu.se Department of Ecology, Swedish University of Agricultural Sciences, P.O. Box 7072, SE-750 07 Uppsala, Sweden

be applied at newly harvested sites, it might be important to consider effects of the treatment on competing vegetation regarding the net effect on conifer growth.

A number of studies have investigated the effect of wood ash application on the biomass of different plant groups, and both positive and negative effects have been reported (Kellner and Weibull 1998; Jacobson and Gustafsson 2001; Arvidsson et al. 2002; Ozolinčius et al. 2007). Positive effects of wood ash on the biomass and cover of specific plant groups may be due to a direct effect on the availability of growth-enhancing nutrients (e.g. phosphorus (P) and potassium (K)). This has been observed on peat soils (Huotari et al. 2007, 2009, 2015). Positive effects of wood ash may also depend on the alkaline wood ash increasing mineralisation of N and P (Rosenberg et al. 2010). Negative effects have been attributed to damage to roots due to high salt concentrations brought about by the treatments (cf. Arvidsson et al. 2002) or may depend on lower rates of net N mineralisation or higher rates of N immobilisation due to wood ash treatment (Jacobson et al. 2014). On newly harvested sites, it is important to consider its effects on both the competing natural vegetation and the established conifer crop, since several other species present could compete for nutrients, e.g. species of birch (*Betula* spp.) or grass. Thus, the net effect of a given nutrient amendment on conifer growth will depend on how competitors respond to the amendment. Therefore, it is of interest to test different types of amendment and the response by competitors in the early stages of forest regeneration.

This study was part of a larger project examining how whole-tree harvesting and nutrient compensation influence young Norway spruce stands (*Picea abies* (L.) Karst.) in south-west Sweden. Previous publications within the project described the effects of nutrient compensation treatments on spruce growth (Wang et al. 2007) and on soil and soil solution chemistry (Wang et al. 2010). The aim of the present study was to test and compare the influence of the application of vitality fertiliser, wood ash and the fine fraction of harvest residues, i.e. green needles and twigs, on the biomass of naturally regenerated birch and field vegetation in a young Norway spruce stand located in an area where atmospheric N deposition is relatively high. Since birch and ground vegetation species are the main competitors to young Norway spruce trees, we tested the hypothesis that the positive effect on plant biomass by the ameliorative treatments is primarily on fast-growing competitive species, i.e. birch and grass (graminoids) species.

Materials and methods

Site description

The experimental area is situated in Skogaby in south-west Sweden (56°33′N, 13°13′E; WGS84), about 16 km from the coast and 95–115 m above sea level. The climate is characterised as maritime-wet, with mean annual precipitation of 1100 mm and mean annual air temperature of 7.5°C. The growing season is about 200 days, from early April to early November (Bergholm et al. 1995).

The Skogaby site received high atmospheric deposition of sulphur (S, 16–20 kg ha^{-1} yr^{-1}) and N over the last few decades of the twentieth century (Bergholm et al. 1995). From 1989 to 1997, mean wet deposition of N was 16.1 kg ha^{-1} y^{-1}, and throughfall of N was 16.6 kg ha^{-1} y^{-1} (Bergholm and Berggren 2001).

The bedrock at the site is gneissic, with a low base mineral content. The soil is a deep (>2 m) sandy loamy till, and the soil type is a poorly developed Haplic podzol. The pH (H_2O) of the humus layer is approximately 3.8, but pH increases to about 4.5 at 10–20 cm depth in the mineral soil. The base saturation of the mineral soil is low (Bergholm et al. 1995).

The present stand is the third generation of coniferous forest on former *Calluna* heathland. The previous stands were Scots pine and then Norway spruce (Bergholm et al. 1995). The bottom layer of the ground vegetation was dominated by bryophyte species. The field layer had frequent wavy hair-grass (*Deschampsia flexuosa* (L.) Trin) and other graminoids. There were also patches of heather (*Calluna vulgaris* (L.) Hull.) and bilberry (*Vaccinium myrtillus* L.).

Experimental design and treatments

Root cuttings of four different clones of Norway spruce (*Picea abies* (L.) Karst) were planted in one block each in 1989, after whole-tree harvesting in winter 1988–1989 of the 25-year-old former Norway spruce stand. Each block consisted of four plots. Different clones of Norway spruce were used to reduce the influence of genetic variability within blocks, but at the same time enable calculations of averages based on several clones. Each plot (10 m × 10 m) was planted with 100 root cuttings, which implied a denser spacing (1 m apart) than normally is used. A fifth clone was planted in a 1-m-wide border zone between the plots. The initial height of spruce (measured 1991) differed systematically between the clones used. In addition to genetic variability, this difference was also expected to reflect variability in soil quality between plots. "Initial height of spruce" was a good predictor of spruce height at a later sampling of spruce in 1995 (Wang et al. 2007). The experimental treatments were (1) granulated wood ash (Ash), applied at a dose of 4150 kg dry weight (dw) ha^{-1}, (2), the N-free fertiliser "SkogVital" (Vitality), applied in two doses six months apart, each of 1500 kg ha^{-1} and (3) the fine fraction of harvest residues (Residues), applied at 15,000 kg dw ha^{-1}. A control that received no amendment (Control) was also included. The wood ash was obtained from a municipal heating plant at Eskilstuna and was well combusted, with loss on ignition of 4.5% at 550°C. To make the wood ash safer and easier to handle, it was stabilised (hardened) by the addition of water and a small amount of cement (4%) and granulated in a rotating drum (for more information, see Wang et al. 2007, 2010). The Vitality fertiliser was a commercial product (manufactured by Yara, Landskrona, Sweden) containing dolomite (Ca, Mg) and sulphates, with P in the form of apatite (50%) and superphosphate (50%), and K in the form of KCl (Table 1). The Residues treatment consisted of the nutrient-rich, fine fraction of Norway spruce biomass left on-site at harvest. It was produced by separating the green needles and small-diameter branches

Table 1. Time of application of compensatory nutrient treatments (Residues, Ash and Vitality), duration of the treatments before ground vegetation (Veg.) and birch was sampled, and amounts of elements applied in the treatments. Note: Duration is not identical to full growing seasons since vegetation was sampled in October/November 1995 and birch was sampled in September 1997.

Treatment	Application	During (years) Veg.	Birch	N	P	K	Ca	Mg	S	B
Residues	July-92	3	5	185	15	46	65	16	15	0.3
Wood ash	July-91	4	6	0	33	166	581	62	5	1.3
Vitality 1	Oct-91	4	6	0	75	45	315	72	120	1.5
Vitality 2	June-92	3	5	0	75	45	315	72	120	1.5

from the stems and coarser branches, followed by chipping of the fine fraction (physical dimension up to approx. 5 cm). The aim was to obtain a fraction as similar as possible to that available in a practical situation, where fine and nutrient-rich fractions of chips are separated from pure woodchips during chipping in the field (Wang et al. 2007).

The nutrient load applied in the Residues treatment corresponded approximately to the nutrient content in residues following the final felling of Norway spruce stands in the region, i.e. site T103, Tönnersjöheden, in Björkroth and Rosén (1977). The doses in the Ash and Vitality treatments were designed to compensate for ash and nutrient removal through whole-tree harvesting, based on ash and element contents in the harvested biomass (e.g. Eriksson 1998). Thus, the wood ash dose (4150 kg dw ha^{-1}) exceeded the current official recommendation of a maximum of 2000–3000 kg wood ash per ha over a 10-year period (Swedish Forest Agency 2019). However, for most nutrients (K, Ca, Mg), the dose was within the range extracted during intensive harvesting at a productive site (Olsson and Westling 2006). Total amounts of macronutrients and micronutrients added in each treatment are shown in Table 1.

The granulated wood ash was applied as uniformly as possible by hand to each plot in July 1991 two years after replanting. The vitality fertiliser was applied by hand on two occasions, in October 1991 and June 1992. The chipped residues were uniformly applied by hand on top of the ground vegetation in July 1992, one year after the application of wood ash in the Ash treatment (Table 1). The amount of residues applied was 1.5 kg d.m. m^{-2}. The different timing of the treatments was due to practical constraints.

Birch biomass sampling and preparation

Birch (*Betula* spp.) dominated among tree species that established spontaneously following clear-felling in winter 1988–1989. Both *Betula pubescens* Ehrh. and *B. pendula* Roth. occurred at the site, but were not separated by species in this study. The number of birch seedlings varied among plots at the time of replanting (1989). In September 1997, the diameters of all stems of birch trees taller than 1.3 m were recorded by cross-callipering at stem base (0.1 m, D_B) and breast height (1.3 m, D) above the soil surface. In each plot, the dataset of birch was then divided into diameter classes ($n = 6$) based on the average diameter (D). These classes were <0.4 cm, 0.5−1.4 cm, 1.5–2.4 cm and $X + 0.1$ to $X + 0.9$ cm, where X is the upper limit of the previous class. Destructive sampling of birch was carried out in April 1998, and foliage was thus not included. In each plot, one birch tree was randomly selected from each diameter class for destructive sampling. The sample tree was cut at the soil surface, and height was recorded. Two branches, one from the upper half of the crown and the other from the lower half, were taken for dry weight determination (see below). All branches were then cut from the stem, and the fresh weight was recorded. Three stem discs (length 5 cm) were taken from the stem, at 10%, 50% and 90% of the distance from the base of the tree, for the determination of dry weight, and the fresh weight of the remaining stem was recorded. For a selection of the sample trees, the stump, including coarse roots, was extracted and fresh weight was determined. Subsamples from the stump and coarse roots were taken for the determination of dry weight. Branches, stem discs and subsamples of the stump and coarse roots were dried at 85°C for at least 48 h to obtain dry weight.

To calculate the total dry mass of birch per unit area, it was assumed that all trees recorded in each diameter class had the same dry weight biomass as the sample tree. Thus, by multiplying the biomass of the sample tree from each diameter class by the number of trees in that class, the total biomass of birch in each diameter class in each plot was calculated. The total biomass of birch in 1997 in each plot was then obtained by adding up the biomass from each diameter class.

An allometric relationship was used to describe the biomass of different parts of birch trees following the procedure of Claesson et al. (2001). The dry mass (g) of each biomass (B) fraction was described using Equation (1), where H (cm) is tree height, D_B (cm) is diameter at stem base, and a and b are the constant and coefficient:

$$\ln(B) = a + b\ln(D_B^2 H). \qquad (1)$$

Ground vegetation biomass sampling and preparation

Ground vegetation was sampled in October/November 1995 four years after wood ash application and three years after the addition of Vitality fertiliser and residue treatments. In each plot, eight square subsamples (20 cm × 20 cm) were taken at even spacing along the diagonals of the plot, with the restriction that no subsample was taken closer than 30 cm to a spruce tree. Thus, all ground vegetation biomass data are for the plot area (72%), where the area close to spruce has been excluded. All aboveground field- and bottom-layer vegetation were sampled. The vegetation materials from the eight small squares were pooled to one composite sample per plot. In the laboratory, the samples were first sorted into six types of vegetation, i.e. *Calluna vulgaris*, *Vaccinium myrtillus* L., herbs, graminoids, mosses and lichens. For further analyses, ground vegetation plants were pooled into three groups: bottom-layer (mosses and lichens), dwarf shrubs (whole aboveground plant), graminoids. The bottom-layer category was dominated by mosses, since lichens only occurred with small cover. Samples of *C. vulgaris* and *V. myrtillus* were lumped together as "dwarf shrubs", where *C. vulgaris* was the dominant fraction. "Graminoids" were dominated by *D. flexuosa*. Since the biomass of herbs was generally low and herbs were only detected in seven of the 16 plots, herbs were not considered further in the study. The samples were weighed to determine the fresh weight of each fraction on the basis of area, and subsamples were then dried at 70°C for 48 h to determine the dry weight of the material.

Root sampling and preparation

Beside the sampling of stumps and coarse roots of birch, fine roots from all species were sampled by coring in October/November 1995, i.e. the year of the ground vegetation assessment. In each plot, 16 soil cores (diameter 4.5 or 6 cm), which included the organic horizon, were sampled at regular intervals along the diagonals of the plots. Each soil core was cut into four 5-cm sections: 0–5 cm, 5–10 cm, 10–15 cm and 15–20 cm. The samples from each soil horizon were pooled per plot, and the soil cores were then transported to the laboratory and stored at −20°C until preparation. Roots from each composite soil horizon sample were sorted according to four categories: "Norway spruce live roots", "graminoid roots", "dwarf-shrub roots" and "unidentified roots". Birch fine roots were not actively discerned and were assumed to be contained in the group "unidentified roots". Moreover, the "dwarf-shrub roots" category was expected to contain a large proportion of birch fine roots, due to the similar appearance. The groups "dwarf-shrub roots" and "unidentified roots" were therefore combined to form the group "unidentified woody roots". Root samples were washed free from soil, sorted, dried at 70 °C for 48 h and weighed.

Chemical analysis

Chemical analyses were performed on milled aboveground parts of the dwarf shrubs, graminoids and bottom-layer groups. Subsamples of 400 mg (dry weight) of each group were digested in an HNO_3:$HClO_4$ solution (10:1), and the digest was then analysed using inductively coupled plasma spectroscopy (ICPS) (Elan 5000, Perkin Elmer, Norwalk, CT, USA). The N contents in the different fractions were analysed with a Carlo-Erba element analyser (Modell, P-E 2400, Perkin Elmer, CT, USA).

Statistical analysis

The effect of nutrient compensation treatment on birch and ground vegetation biomass and on nutrient concentrations in biomass was analysed using the general linear model in MINITAB (version 19), with nutrient compensation treatment (4 levels) as the independent variable. The continuous variable "initial height of spruce" (Wang et al. 2007) was used as a co-variable in the analysis. To test whether allometric regression functions differed between treatments, the analysis of co-variance was done, where treatment was used as a categorical variable and D_B^2H used as co-variate. In the calculations, D_B and H were expressed in cm. The Tukey pairwise comparison test was used to test whether means differed significantly ($\alpha = 0.05$) (Tukey 1949).

Results

Effects on biomass

For the time of application, duration and dose of elements in the treatments, see Table 1. Note that the sampled area is a subset (72%) of the total plot area since the area within 0.3 m from spruce trees was excluded.

An ANCOVA test of Equation (1) revealed no significant difference between treatments in the allometric relationship for birch. Therefore, for all treatments we used the following constants and coefficients in Equation (1) for branch biomass: $a = -2.42$, $b = 0.922$ ($R^2 = 93.4\%$), and stem wood biomass: $a = -1.20$, $b = 0.864$ ($R^2 = 97.7\%$).

The total biomass of birch ranged 100–400 g m^{-2}, where mean values were the lowest in the Ash treatment and the highest in the Vitality treatment. However, there was no significant effect of treatments on the aboveground biomass, coarse roots or total biomass of birch (Figure 1(a)). No significant treatment effect was revealed for birch tree density and D_B, D and D_B^2H (Table 2).

The effects of treatment on graminoid root biomass ($p = 0.005$) and total biomass ($p = 0.010$) were statistically significant. The biomass of these fractions was the greatest in the Ash treatment and the smallest in the Control (Figure 1(b)). Furthermore, graminoid aboveground biomass was the greatest in the Vitality treatment and the smallest in the Control (Figure 1(b)). However, aboveground graminoid biomass was smaller than the root biomass, reflecting the fact that sampling was conducted in autumn when aboveground shoots were partly senescent. There were no significant treatment effects on the biomass of dwarf shrubs and the bottom layer (Figure 1(c)).

The biomass of unidentified woody roots captured by coring down to 15 cm soil depth was 73 g·m^{-2} in the Control, 67 g·m^{-2} in the Residues, 61 g·m^{-2} in the Ash and 111 g·m^{-2} in the Vitality treatments. The majority of root biomass was concentrated to the 0–5 cm soil layer (O/A-horizon). The proportion of roots in the top 0–5 cm as a percentage of the total mass of roots to 15 cm is shown in Figure 2, where the fine root (<2 mm) biomass of spruce is given as reference. The root biomass in the 15–20 cm layer was generally very low or negligible except in one plot, which had the main proportion of roots in the 15–20 cm layer. However, only roots to 15 cm depth were considered in the study.

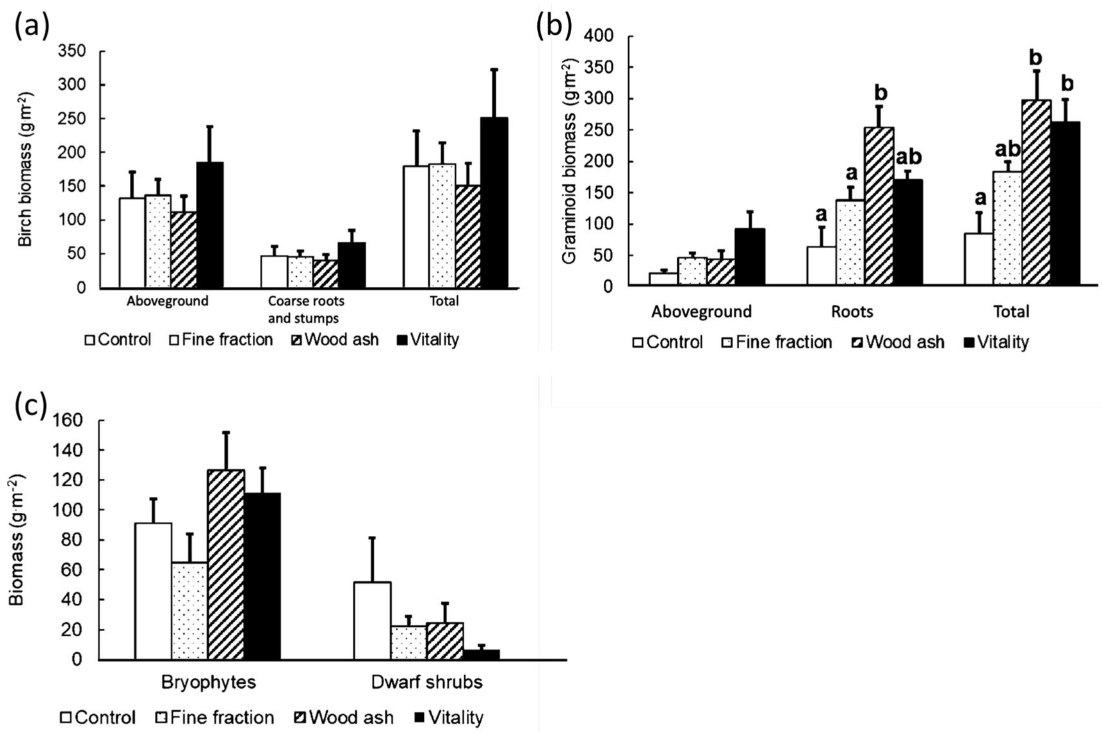

Figure 1. (a) Aboveground biomass, biomass of coarse roots and stumps and total biomass of birch (*Betula* spp.); (b) aboveground biomass, biomass of fine roots and total biomass of graminoids (*Deschampsia flexuosa*) and (c) aboveground biomass of dwarf shrubs and the bottom layer. Error bars show standard error. Means marked with different letters are significantly different according to Tukey's pairwise test.

Effects on element concentrations in aboveground biomass

The concentration of nutrients in biomass varied between the different plant groups and the effect of treatment was statistically significant in a few cases: phosphorous (P) in the bottom layer, and calcium (Ca) and magnesium (Mg) in graminoids (Table 3).

The concentration of P in the bottom-layer biomass was significantly higher in the Vitality treatment than the Ash and Control treatments (Table 3). The Vitality treatment also resulted in significantly higher Ca concentrations in graminoids compared to Ash and Control, and higher Mg concentrations than in Ash treatment. Compared to other treatments, the mean Ca concentration in the bottom-layer biomass of the Vitality treatment was higher; this difference was close to statistically significant ($p = 0.063$). The concentrations of N, sulphur (S), zinc (Zn) and boron (B) in biomass did not depend on treatment for any plant group or plant fraction (Table 3).

Discussion

The most significant response by natural vegetation to the nutrient compensation treatments tested in this study was a positive effect of the Ash and Vitality treatments on graminoid biomass. Birch biomass and height were unresponsive to all treatments. At the same forest site, Wang et al. (2007) also found that spruce height growth had not responded to any of the treatments.

It has frequently been reported that liming and wood ash applications lead to increases in pH in acid forest soils, and associated increases in Ca concentrations, and that growth and abundance of *D. flexuosa* were simultaneously enhanced by these treatments (Hallbäcken and Zhang 1998; Arvidsson et al. 2002; Bergholm et al. 2015; Kindtler et al. 2019). At our study site, the Vitality treatment was the only treatment associated with significant increases in pH and concentrations of Ca and Mg in the humus compared with the Control (Table 4). The C/N ratio of the humus layer did not depend on treatment (Table 4). However, the actual range

Table 2. Birch (*Betula* spp.) data from sampling in September 1997 after 5(6) years of treatment duration (see Table 1). Average diameter of birch (sample trees) at ground level (0.1 m) and at 1.3 m, tree height, birch density and diameter squared times height (co-variable in the ANCOVA) in compensatory nutrient treatments (Residues, Ash, Vitality). Birch biomass data are for winter conditions with no foliage. Spruce data are from sampling 1995 (Wang et al. 2007). All values shown are means ($n = 4$), with standard deviations given in brackets. n.s. = not significant ($p > 0.05$).

			Birch data			Spruce data
	D_B (0.1 m) (mm)	D (1.3 m) (mm)	H (cm)	N (stems ha^{-1})	$D_B{}^2H$	Height (cm)
Control	26.1 (3.4)	10.2 (1.8)	220 (24)	4530 (1700)	3680 (5500)	162 (19)
Residues	29.4 (2.7)	12.8 (1.9)	230 (19)	3950 (1300)	4440 (6100)	155 (22)
Ash	25.4 (4.9)	11.0 (3.7)	241 (64)	4250 (2100)	5290 (13000)	155 (24)
Vitality	29.1 (3.6)	12.4 (2.1)	226 (18)	7120 (3100)	4610 (6900)	152 (28)
	p = n.s.	p = n.s.	p = n.s.	p = n.s.	p = n.s.	p = n.s.

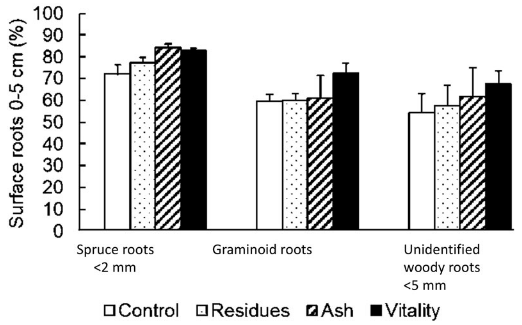

Figure 2. Fine root biomass in the top 0–5 cm soil layer as a percentage of total fine root biomass.

of humus C/N has been associated with several positive (but also negative) average responses, relative to control plots, in terms of stem volume increment after wood ash addition to conifer stands in Sweden (Jacobson et al. 2014). Thus, the positive effect of the Vitality treatment on the biomass of *D. flexuosa* (Figure 1(b)) is in line with previous studies in the present stand (Table 4) and other studies of effects of soluble wood ash and lime amendments.

Effects on nutrient concentrations

The observed increases in the concentrations of Ca and Mg in graminoids and P in mosses in the Vitality treatment (Table 4) reflect the relatively high solubility and high concentrations of these elements in the N-free fertiliser used ("SkogVital"). Similar findings have been made in previous studies of needle and fine root chemistry at the same study site (Table 4). In the present case, it should be noted that late autumn sampling of graminoids (early November) meant that leaf senescence and resorption of nutrients (and leaching in the case of K) had been initiated. Leaf senescence is associated with the loss of mass and thereby an increase in leaf nutrient concentrations (e.g. Ca), whereas resorption leads to a decrease in nutrient concentrations, especially for N and P. The nutrient concentrations given in Table 4 should therefore be considered in light of those facts.

Effects on graminoids

Graminoid biomass was dominated by *D. flexuosa*, which is often the dominant ground vegetation species on acid, well-drained forest soils following clear-cutting in southern Sweden (e.g. Hedwall et al. 2013; Bergholm et al. 2015). The late autumn sampling of *D. flexuosa* probably meant that aboveground biomass and, to some extent, root biomass were lower than in summer conditions (cf. Aerts et al. 1992). The biomass of *D. flexuosa* in the Ash and Vitality treatments (Figure 1) was comparable to that in situations where it is considered a major competitor to conifers (cf. Nilsson and Örlander 1999). Unpublished data on shoot:root ratio from a field study of *D. flexuosa* suggest a value of 1.3 in late summer (August) when only leaves are accounted for, compared with a value of 3 when the biomass of fertile shoots (straw) is included (Bergholm et al. 2015; Bengt Olsson, pers. commun. April 2021). However, taking the biomass of *D. flexuosa* in the control plots as a reference, the relatively low figure indicated that shading from spruce had become important (cf. Strengbom et al. 2004). At the time of sampling of vegetation, spruce height was on average of 1.6 m (Table 2). In addition, spruce planting distance in the trial (1 m) was denser than commonly used in practical forestry.

The positive treatment effect on the biomass of *D. flexuosa* in the Ash treatment was unexpected, since the granulated wood ash did not have any observable effects on humus pH or Ca concentrations in humus (Table 4). Other studies have shown that less soluble wood ash types, e.g. granulated wood ash, indeed have short-term effects on relevant soil chemistry, e.g. ammonium-N (NH_4-N) concentrations in the topsoil (Nieminen et al. 2012). In a short-term pot experiment studying the effects of wood ash on growth and cadmium uptake in *D. flexuosa* in plant–soil microcosms, Kindtler et al. (2019) found that wood ash markedly stimulated the growth of *D. flexuosa*. In that study, shoot biomass of grass in the wood ash treatment was almost twice that in a lime treatment to which the wood ash had been adjusted to give the same acid-neutralising capacity, and thus the same soil pH. Those authors concluded that the greater effect of the wood ash was due to its capacity to enrich the soil with growth-limiting nutrients, although effects on N mineralisation and nitrification were not measured (Kindtler et al. 2019). In addition to direct effects of nutrients in compensatory treatments on growth, it should be noted that N mineralisation could be enhanced by both addition of limiting nutrients and increases in pH (Persson and Wirén 1995; Staaf et al. 1996). Increases in pH also favour the formation of nitrate (NO_3-N), but Wang et al. (2010) found that the concentrations of NO_3-N in different soil layers did not differ between treatments at our study site. Soil water was also sampled in the study by Wang et al. (2010), but not in the first season, so initial effects of the treatments on the N cycle, including NO_3-N, would have been missed. It is likely that *D. flexuosa* has a competitive advantage over species in the other plant groups included in this study as regards the utilisation of any initially formed nitrate (Troelstra et al. 1995). However, the ability to assimilate nitrate is also present in birch, heather and spruce (Friemann et al. 1992; Troelstra et al. 1995; Heiskanen 2005). Another mechanism to consider as regards possible reasons for the positive effects of the Ash and Vitality treatments on *D. flexuosa* is that seedling establishment in acid humus (<pH 4) is enhanced even by a small increase in soil pH (Balsberg-Påhlsson 1995). Wood ash did not affect humus pH at the study site (Table 4), but the ash might have created favourable conditions in terms of pH on top of the humus. To summarise, the effect of Vitality and Ash on graminoid biomass can be an effect that occurs by higher N mineralisation and/or improved site conditions for seedling establishment.

Effects on the bottom layer

The lack of treatment response by bottom-layer species in this study confirmed earlier findings that less soluble types of ash have no negative effect on mosses (cf. Arvidsson

Table 3. Autumnal nutrient concentrations in aboveground parts of graminoids, bottom-layer biomass and dwarf shrubs in the compensatory nutrient treatments (Residues, Ash, Vitality). All values shown are means ($n = 4$), with standard deviations given in brackets. Significant differences ($p < 0.05$) between treatments according to Tukey's test are indicated by different letters (a, b). n.s. = not significant.

	N		P		K		Ca		Mg		S		Zn		B
					($mg\ g^{-1}$)								($\mu g/g^{-1}$)		
Graminoids															
Control	15	(2.1)	1.2	(0.39)	10	(4.1)	0.88	(0.08)a	0.68	(0.12)ab	1.1	(0.16)	49	(8.5)	3.8
Residues	14	(2.9)	1.2	(0.14)	10	(1.5)	1.3	(0.05)ab	0.73	(0.07)ab	1.0	(0.14)	43	(2.6)	3.0
Ash	12	(1.2)	0.97	(0.05)	8.5	(2.2)	1.1	(0.07)a	0.58	(0.06)a	0.90	(0.02)	47	(11)	3.5
Vitality	13	(0.5)	1.3	(0.04)	7.9	(2.2)	1.9	(0.53)b	0.82	(0.07)b	0.98	(0.06)	44	(4.0)	3.0
	p = n.s.		p = n.s.		p = n.s.		$p = 0.005$		$p = 0.017$		p = n.s.		p = n.s.		p = n.s.
Bottom layer															
Control	17	(1.6)	1.1	(0.17)a	5.8	(0.45)	2.2	(0.19)	1.1	(0.09)	1.4	(0.16)	58	(4.1)	4.2
Residues	18	(3.1)	1.3	(0.25)ab	5.6	(0.89)	2.6	(0.35)	1.1	(0.20)	1.3	(0.20)	53	(12)	4.4
Ash	16	(0.2)	1.0	(0.05)a	5.2	(1.1)	2.3	(0.19)	1.0	(0.20)	1.3	(0.03)	53	(6.4)	3.4
Vitality	15	(1.4)	1.5	(0.19)b	6.7	(0.14)	3.4	(0.98)	1.4	(0.21)	1.3	(0.09)	50	(5.6)	3.4
	p = n.s.		$p = 0.002$		p = n.s.		$p = 0.063$		p = n.s.		p = n.s.		p = n.s.		p = n.s.
Dwarf shrubs															
Control	11	(2.5)	0.80	(0.23)	3.7	(0.74)	3.8	(1.8)	1.0	(0.10)	0.91	(0.18)	22	(8.0)	12
Residues	13	(1.2)	1.0	(0.17)	4.3	(0.33)	4.1	(1.3)	1.2	(0.13)	1.0	(0.10)	28	(8.6)	13
Ash	10	(1.1)	0.76	(0.12)	3.8	(0.35)	3.4	(0.95)	1.0	(0.14)	0.95	(0.04)	26	(7.1)	13
Vitality	10	(1.2)	0.80	(0.13)	3.9	(0.60)	2.7	(0.70)	1.1	(0.24)	0.96	(0.22)	16	(0.1)	12
	p = n.s.		p = n.s.		p = n.s.		p = n.s.		p = n.s.		p = n.s.		p = n.s.		p = n.s.

Table 4. Data on element concentrations in current-year needles and fine roots (top 0–5 cm) of Norway spruce compiled from Wang et al. (2007) and organic soil chemical data from Wang et al. (2010).

	Norway spruce tree data from Wang et al. (2007)					
	N mg g^{-1}	P	K	Ca	Mg	Al
Needles C0						
Control	9.45	1.00b	3.30	2.69a	0.74	
Residues	10.45	1.22	4.45	3.08	0.87	
Ash	8.70	0.98b	4.23	3.85	0.83	
Vitality	9.18	1.61a	4.70	4.12b	0.88	
Fine roots (<1 mm) in top 0–5 cm						
Control	12.02	0.95	0.26	3.18b	0.61b	0.51b
Residues	12.4	1.00	0.28	3.47b	0.67	0.38
Ash	11.28	0.86	0.48	3.96b	0.80	0.31
Vitality	10.98	1.00	0.39	5.96a	0.92a	0.27a

	Soil data from Wang et al. (2010)							
	NH_4-N	NO_3-N	C/N cmolc kg^{-1} d.m.	K	Ca	Mg	Al	pH(H_2O)
Litter layer								
Control	6.5b	0.19	28.0	2.68ab	10.0ab	4.47	0.33	4.89
Residues	36.2a	0.54	28.2	2.51ab	10.06ab	3.88	0.54	4.88
Ash	8.2b	0.37	29.2	3.99a	7.25b	4.04	0.57	4.79
Vitality	10.8b	0.85	34.9	2.37b	21.35a	6.98	0.35	5.19
Humus layer								
Control	17.8	0.00	28.8	0.74	10.12b	3.98b	2.71b	3.76b
Residues	10.1	0.23	27.5	0.70	10.44b	4.08b	2.41b	3.94b
Ash	3.7	0.00	27.8	0.77	8.52b	3.11b	3.16b	4.02ab
Vitality	13.9	0.14	27.9	0.74	27.83a	6.76a	0.68a	4.59a

et al. 2002). The more soluble Vitality fertiliser had no effect on the biomass of the bottom layer but was apparently a source of P, as indicated by the higher concentrations of P in the bottom-layer biomass (Table 3). The observed N concentration of 17.4 g kg^{-1} in the biomass of bottom layer in Control plots in the present study (Table 3) confirmed that the Skogaby site receives N loads above the European average (cf. Schröder et al. 2010). It has been demonstrated that P fertilisation increases P concentrations in mosses in N-enriched environments (Arróniz-Crespo et al. 2008). In our case, the bottom layer was the only plant group that responded to nutrient compensation (Vitality treatment) in terms of increases in P concentrations in biomass (Table 3). The Ash treatment did not affect the P concentration in the bottom layer, probably because the P content of the wood ash used was considerably lower than that of the Vitality fertiliser (Table 2) and the wood ash dose was not large enough to act as a direct source of P. It should also be noted that hardened wood ash has a low rate of dissolution (Eriksson 1998; Steenari et al. 1998, 1999).

Effects on dwarf shrubs

The dwarf shrub (*Calluna vulgaris* (L.)) dominated markedly over *V. myrtillus* in the present study, and the results on dwarf shrubs therefore essentially represent effects on *C. vulgaris*. This species occurs naturally on base-depleted soils, but it is often absent from environments where Ca availability is high (Gimingham 1960; Leake and Read 1989). In a study examining the effects of crushed self-hardened wood ash on vegetation cover, Arvidsson et al. (2002) found that the two wood ash treatments used, which differed in origin and chemical composition, had different suppressive effects on the cover of heather. Those authors attributed this to the different salt content of the ashes. In the present study, the aboveground biomass of dwarf shrubs was particularly low in the Vitality treatment (non-significantly), possibly indicating a non-optimal increase in soil pH and Ca availability (cf. Leake and Read 1989) (Figure 1(c)).

Effects on birch

Birch (*Betula* spp.) is early successional species adapted to a wide range of site conditions and may rapidly colonise forest sites subjected to catastrophic disturbance by windthrow or forest fire. The rapid growth of birch in early successional stages requires it to be competitive for soil nutrient resources. Birch has been found to respond to wood ash amendments on peat soils (Huotari et al. 2015), but there are few studies on mineral soils. However, the nutrient compensation treatments tested in the present study did not affect birch height, birch biomass or distribution of birch biomass in this time frame. Thus, our hypothesis was not supported in the case of birch. The observed difference between birch and *D. flexuosa* in terms of response in growth was probably not due to differences in root distribution, since fine roots were generally concentrated to the topsoil (0–5 cm layer) (Figure 2) and treatment effects regarding nutrient release or indirect effects on N mineralisation could be expected to be strongest in the top part of the humus layer. The category "unidentified woody roots" most likely contained the main part of birch fine roots, suggesting that also birch fine roots and nutrient uptake were concentrated to the surface (cf. Brandtberg et al. 2000; Curt and Prévosto 2003; Brandtberg et al. 2004; Kalliokoski 2011).

The Residues treatment did not lead to any significant effect on the biomass of birch or of any other plant group in this time frame. The NH_4-N concentration in the litter layer was significantly higher in the Residues treatment than in the other treatments three years after application (Table 4), indicating that this layer had reached a stage of net N release. The lack of response for all plant groups in this study (Figure 1) indicates that nutrient release from the Residues in the shorter term was quantitatively unimportant for the growth of the plants included in this study. However, long-term effects are plausible.

It should be noted that *D. flexuosa* is often established at forest sites before clear-felling, since it can survive even in dense forests. Birch, on the other hand, mostly establishes through seeds shed by trees in the vicinity (Granström 1986). Therefore, the existing *D. flexuosa* plants may have a competitive advantage over birch as regards soil resources provided by nutrient compensation treatments in the initial phase after clear-felling.

Conclusions

Over the study period of 3–6 years, both granular hardened wood ash and commercial N-free vitality fertiliser enhanced the growth of graminoids (*D. flexuosa*), but not that of birch (*Betula* spp.), in a newly established spruce stand on podzolic mineral soil in an area of Sweden affected by atmospheric N deposition. Green forest residues had no significant effect on the growth of birch or graminoids in the short term. None of the three amendments tested had any significant effects on the growth of dwarf shrubs (e.g. heather (*C. vulgaris*)), which are native plants best adapted to acidic soil conditions. Thus, competition from naturally regenerating *D. flexuosa* can increase in the short term when using nutrient amendments such as vitality fertiliser or the less soluble granulated wood ash.

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References

Aerts R, Bakker C, de Caluwe H. 1992. Root turnover as determinant of the cycling of C, N, and P in a dry heathland ecosystem. Biogeochem. 15:175–190.

Akselsson C. 2005. Regional nutrient budgets in forest soils in a policy perspective. Doctoral Thesis. Dept. Of Chemical Engineering, Lund Institute of Technology. 2005:3 Lund, Sweden.

Akselsson C, Belyazid S. 2018. Critical biomass harvesting – applying a new concept for Swedish forest soils. For Ecol Manage. 409:67–73.

Andersson FO, Lundkvist H. 1989. Long- term Swedish field experiments in forest management practices and site productivity. In: Dyck WJ, Mees CA, editor. Research strategies for long-term site productivity. Proceedings IEA/BE A3 Workshop, Seattle, WA. Aug. 1988. IEA/BE A3 Rep. 8. New Zealand Forest Research Institute Bulletin 152. p. 125–137. New Zealand: Rotorua.

Arróniz-Crespo M, Leake JR, Horton P, Phoenix GK. 2008. Bryophyte physiological responses to, and recovery from, long-term nitrogen deposition and phosphorus fertilisation in acidic grassland. New Phytol. 180:864–874.

Arvidsson H, Vestin T, Lundkvist H. 2002. Effects of crushed wood ash application on ground vegetation in young Norway spruce stands. For Ecol Manage. 161:75–87.

Balsberg-Påhlsson AM. 1995. Growth, radicle and root hair development of *Deschampsia flexuosa* (L.) trin. seedlings in relation to soil acidity. Plant Soil. 175:125–132.

Bergholm J, Berggren D. 2001. Hur försurades marken? studier av deposition, mark och markvatten. In: Persson T, Nilsson LO, editor. Skogabyförsöket – effekter av långvarig kväve-och svaveltillförsel till ett skogsekosystem. Naturvårdsverket Rapport 5173. p. 25–50. Swedish: Stockholm.

Bergholm J, Jansson PE, Johansson U, Majdi H, Nilsson LO, Persson H. 1995. Air pollution, tree vitality and forest production-The Skogaby project. In: Nilsson LO, Huttl RF, Johansson UT, Mathy P, editors. *Nutrient uptake and cycling in forest ecosystems*. Dordrecht: Springer; p. 69–87.

Bergholm J, Olsson BA, Vegerfors B, Persson T. 2015. Nitrogen fluxes after clear-cutting. ground vegetation uptake and stump/root immobilization reduce N leaching after experimental liming, acidification and N fertilization. For Ecol Manage. 342:64–76.

Björkroth G, Rosén K. 1977. Biomassa och näringsmängder på fyra ståndorter. PHU report 49. Umeå, Sweden: Swedish University of Agricultural Sciences. 20 p. In Swedish.

Börjesson P, Gustavsson L, Christersson L, Linder S. 1997. Future production and utilisation of biomass in Sweden: potentials and CO2 mitigation. Biomass Bioenerg. 13:399–412.

Brandtberg PO, Lundkvist H, Bengtsson J. 2000. Changes in forest-floor chemistry caused by a birch admixture in Norway spruce stands. For Ecol Manage. 130:253–264.

Brandtberg PO, Lundkvist H, Bengtsson J. 2004. Distributions of the capacity to take up nutrients by *Betula* spp. and *Picea abies* in mixed stands. For Ecol Manage. 198:193–208.

Claesson S, Sahlén K, Lundmark T. 2001. Functions for biomass estimation of young pinus sylvestris, Picea abies and Betula spp. from stands in northern Sweden with high stand densities. Scand J For Res. 16:138–146.

Curt T, Prévosto B. 2003. Rooting strategy of naturally regenerated beech in silver birch and Scots pine woodlands. Plant Soil. 255:265–279.

De Jong J, Akselsson C, Egnell G, Löfgren S, Olsson B. 2017. Realizing the energy potential of forest biomass in Sweden – How much is environmentally sustainable? For Ecol Manage. 383:3–16.

Eriksson HM. 1998. Short-term effects of granulated wood ash on the forest soil chemistry in SW and NE Sweden. Scand J For Res Suppl. 2:43–55.

Forsum Å, Olsson O, Sahlin M. 2018. Sweden – 2018 update. Bioenergy policies and status of implementation (Ed. Pelkmans L). https://www.ieabioenergy.com/iea-publications/country-reports/2018-country-reports/.

Friemann A, Lange M, Hachtel W, Brinkmann K. 1992. Induction of nitrate assimilatory enzymes in the tree *Betula pendula*. Plant Physiol. 99:837–842.

Gimingham CH. 1960. Biological flora of the British isles. *Calluna* salisb. J Ecol. 48:455–483.

Granström A. 1986. Seed banks in forest soils and their role in vegetation succession after disturbance. PhD Thesis No. 6, Swedish University of Agricultural Sciences, Umeå.

Hallbäcken K, Zhang LQ. 1998. Effects of experimental acidification, nitrogen addition and liming on ground vegetation in a mature stand of

Norway spruce (Picea abies (L.) karst.) in SE Sweden. For Ecol Manage. 108:201–213.

Hannam KD, Allen VD, Deschamps E, Jull M, Kwiaton M, McKenney D, Rutherford PM, Hazlett PW. 2018. Wood ash a soil amendment in Canadian forests: what are the barriers to utilization. Can J For Res. 48:442–450.

Hedwall P-O, Grip H, Linder S, Lövdahl L, Nilsson U, Bergh J. 2013. Effects of clear-cutting and slash removal on soil water chemistry and forest-floor vegetation in a nutrient optimised Norway spruce stand. Silva Fenn. vol. 47 no. 2 article id 933. https://doi.org/10.14214/sf.933.

Heiskanen J. 2005. Effect of nitrate and ammonium on growth of transplanted Norway spruce seedlings: a greenhouse study. Ann Bot Fenn. 42:1–9.

Huotari N, Tillman-Sutela E, Kauppi A, Kubin E. 2007. Fertilization Ensures Rapid Formation of Ground Vegetation on cut-Away Peatlands. Can J For Res. 37:874–883.

Huotari N, Tillman-Sutela E, Kubin E. 2009. Ground vegetation exceeds tree seedlings in early biomass production and carbon stock on an ash-fertilized cut-away peatland. Biomass Bioen. 33:1108–1115.

Huotari N, Tillman-Sutela E, Moilanen M, Laiho R. 2015. Recycling of ash – For the good of the environment? For Ecol Manage. 348:226–240.

Jacobson S, Gustafsson L. 2001. Effects on ground vegetation of the application of wood ash to a Swedish Scots pine stand. Bas Appl Ecol. 2:233–241.

Jacobson S, Lundström H, Nordlund S, Sikström U, Pettersson F. 2014. Is tree growth in boreal coniferous stands on mineral soils affected by the addition of wood ash? Scand J For Res. 29(7):675–685.

Kalliokoski T. 2011. Root system traits of Norway spruce, Scots pine, and silver birch in mixed boreal forests: an analysis of root architecture, morphology and anatomy. Dissertationes Forestales 121. 67 p. http://www.metla.fi/dissertationes/df121.htm.

Kellner O, Weibull H. 1998. Effects of wood ash on bryophytes and lichens in a Swedish pine forest. Scand J For Res Suppl. 2:76–85.

Kimmins JP. 1976. Evaluation of the consequences for future tree productivity of the loss of nutrients in whole-tree harvesting. For Ecol Manage. 1:169–183.

Kindtler NL, Ekelund F, Rönn R, Kjöller R, Hovmand M, Vestergård M, Christensen S, Johansen L. 2019. Wood ash effects on growth and cadmium uptake in *Deschampsia flexuosa* (wavy hair-grass). Envir Pollut. 249:886–893.

Leake JR, Read DJ. 1989. The biology of mycorrhiza in the ericaceae XV. The effect of mycorrhizal infection on calcium uptake by *Calluna vulgaris* (L.) hull. New Phytol. 113:535–544.

Levin R, Eriksson H. 2010. Good-practice guidelines for whole-tree harvesting in Sweden: moving science into policy. *For Chron*. 86:52–56.

Lundmark A, Athanassiadis D, Wetterlund E. 2015. Supply assessment of forest biomass – A bottom-up approach for Sweden. *Biom Bioen.* 75:213–226.

Mälkönen E. 1976. Effect of whole-tree harvesting on soil fertility. *Silva Fenn.* 10:157–164.

Nieminen JK, Räisänen M, Haimi J. 2012. Spot mounding and granulated wood ash increase inorganic N availability and alter key components of the soil food web in clear-cut Norway spruce forests. *For Ecol Manage.* 263:24–30.

Nilsson U, Örlander G. 1999. Vegetation management on grass-dominated clearcuts planted with Norway spruce in southern Sweden. *Can J For Res.* 29:1015–1026.

Olsson BA, Westling O. 2006. Skogsbränslecykelns näringsbalans. (The element mass balance of the forest energy – wood ash cycle) (Swedish with English summary) The Swedish Environmental Research Institute (IVL) Report B 1669. Stockholm, 34 pp.

Ozolinčius R, Varnagirytė-Kabašinskienė I, Stakėnas V, Mikšys V. 2007. Effects of wood ash and nitrogen fertilization on Scots pine crown biomass. Biom Bioen. 31:700–709.

Persson T, Wirén A. 1995. Nitrogen mineralization and potential nitrification at different depths in acid forest soils. Plant Soil. 168–169. 55–65.

Rosenberg O, Persson T, Högbom L, Jacobson S. 2010. Effects of wood-ash application on potential carbon and nitrogen mineralization at two forest sites with different tree species, climate and N status. For Ecol Manage. 260:511–518.

Rothpfeffer C, Karltun E. 2007. Inorganic elements in tree compartments of *Picea abies* –concentrations versus stem diameter in wood and bark and concentrations in needles and branches. Biomass Bioen. 31:717–725.

Schröder W, Holy M, Pesch R, Harmens H, Fagerli H, Alber R, Coskun M, De Temmerman L, Frolova M, González-Miqueo L, et al. 2010. First Europe-wide correlation analysis identifying factors best explaining the total nitrogen concentration in mosses. Atm Env. 44:3485–3491.

Staaf H, Andersson F, Hallbäcken L, Nihlgård B, Nilsson SI, Persson T, Rosen K, Sverdrup H. 1996. Hur uppskattar man åtgärdsbehovet? In: Staaf H, Persson T, Bertills U, editor. Skogsmarkskalkning, resultat och slutsatser från naurvårdsverkets försöksverksamhet. Stockholm: National Swedish Environmental Protection Board; Report 4559, p. 219–233 (In Swedish with English summary).

Steenari BM, Karlsson LG, Lindqvist O. 1999. Evaluation of the leaching characteristics of wood ash and the influence of ash agglomeration. Biom Bioen. 16:119–136.

Steenari BM, Marsic N, Karlsson LG, Tomsic A, Lindqvist O. 1998. Long-term leaching of stabilized wood ash. Scand J For Res Suppl. 2:3–16.

Strengbom J, Näsholm T, Ericsson L. 2004. Light, not nitrogen, limits growth of the grass *Deschampsia flexuosa* in boreal forests. Can J Bot. 82:430–435.

Swedish Forest Agency. 2019. Regler och rekommendationer för skogsbränsleuttag och kompensationsåtgärder. Rapport. 13, 32 pp (In Swedish).

Troelstra SR, Wagenaar R, Smant W. 1995. Nitrogen utilization by plant species from acid heathland soils II. growth and shoot/root partitioning of $N0_3$ assimilation at constant low pH and varying $N0_3\_/NH_4^+$ ratio. J Exp Bot. 46(290):1113–1121.

Tukey J. 1949. Comparing individual means in the analysis of variance. Biometrics. 5(2):99–114.

Verkerk PJ, Fitzgerald JB, Datta P, Dees M, Hengeveld GM, Lindner M, Zudin S. 2019. Spatial distribution of the potential forest biomass availability in Europe. For Ecosyst. 6(5):1–11.

Wang P, Olsson BA, Arvidsson H, Lundkvist H. 2010. Short-term effects of nutrient compensation following whole-tree harvesting on soil and soil water chemistry in a young Norway spruce stand. Plant Soil. 336:323–336.

Wang P, Olsson BA, Lundkvist H. 2007. Effects of wood ash, vitality fertilizer and logging residues on needle and root chemistry in a young Norway spruce stand. Scand J For Res. 22:136–148.

Weetman GF, Webber B. 1972. The influence of wood harvesting on the nutrient status of two spruce stands. Can J For Res. 2:351–369.