Dissolution of granulated wood ash examined by in situ incubation: Effects of tree species and soil type

I. Callesen[a,b,*], M. Ingerslev[a], K. Raulund-Rasmussen[a]

[a]*Forest and Landscape Denmark, University of Copenhagen, Hørsholm Kongevej 11, DK-2970 Hørsholm, Denmark*
[b]*Risoe National Laboratory, Department of Biosystems, DTU, P.O. Box 49, Frederiksborgvej 399, DK-4000 Roskilde, Denmark*

Abstract

Wood ash recycling to forests may counteract nutrient losses caused by biomass harvest, since most nutrients except nitrogen are largely retained in the ash. Raw wood ash has an alkaline reaction with water and contains easily soluble as well as resistant compounds. Ash can be treated to ease handling and to avoid undesired effects on vegetation and leaching of nutrients. Forest ecosystems with different tree species and soils provide variable conditions for mineral dissolution with respect to pH, amount of organic ligands and humidity in the forest floor and the top soil. To study the effects of tree species and soil type on wood ash dissolution, granulated wood ash with particle size 2–4 mm was incubated in situ for 7 years in polyamide mesh bags. The bags were placed under the organic horizon of beech, oak, Norway spruce and Douglas-fir on a nutrient poor soil (*typic Haplorthod*) and a nutrient-rich soil (*oxyaquic Hapludalf*) in Denmark. After 7 years of incubation, the weight loss of the wood ash granulates was 20% in both soil types. Nutrient losses determined by total element analysis were about 35% for calcium, magnesium and potassium and 19% for phosphorus, regardless of tree species or soil type. Incubation for 7 years could not demonstrate possible effects of tree species and soil type on the dissolution of granulated wood ash incubated in mesh bags. The missing effect of tree species and soil type is suggested to be an effect of the incubation method and the pre-treatment of the ash tested here using cement as a binder. Across this broad range in chemical weathering environment the granulated wood ash dissolved at a rather slow rate, suggesting that this ash will have a negligible impact on the soil environment.
© 2007 Elsevier Ltd. All rights reserved.

Keywords: Wood ash; In situ study; Mesh bag; Incubation; Tree species; Nutrient recycling; Bioenergy

1. Introduction

Removal of needles and branches by intensive biomass utilisation in e.g. whole tree harvest may reduce the nutrient capital of the forest ecosystem considerably.

If the wood ash is recycled after incineration of tree biomass, the loss of base cations and phosphorus can be partly compensated. Raw wood ash is highly reactive and alkaline, whereas treated wood ash may be less reactive [1]. Treatment of raw wood ash involves mixing with water, which will cause agglomeration and decreased reactivity of the ash. Ash treatment methods include self-hardening and crushing, granulation and pelletisation [2]. Mixing of ash with additives or with other waste products can improve the stability or nutrient content and thus the fertiliser quality of the ash. Factors that are known to influence the dissolution of soil minerals are soil acidity and the concentration of dissolved organic matter [3–6]. Dissolution of wood ash that is spread over the forest floor is likely to be influenced by the same factors. In this study, we test the hypothesis that tree species and soil type affect dissolution of granulated wood ash in the forest floor.

The environment for dissolution of materials such as ash may be studied by in situ incubation in the soil or in the forest floor. Bags made out of durable, closely woven fabric with degradable materials placed inside are buried in the soil or in the forest floor. The fabric can be penetrated by gas, soil solution, microbes and mycorrhizal hyphae, but

*Corresponding author. Department of Biosystems, Risoe National Laboratory, DTU, P.O. Box 49, Frederiksborgvej 399, DK-4000 Roskilde, Denmark. Tel.: +45 4677 4107; fax: +45 4677 4109.

E-mail addresses: ingeborg.callesen@risoe.dk (I. Callesen), moi@life.ku.dk (M. Ingerslev), krr@life.ku.dk (K. Raulund-Rasmussen).

Table 1
Soil nutrient pools and normal climate (1961–90) at Ulborg (ULB) and Christianssæde (CHR)

Site	Temp. (°C)	Prec. (mm)	Clay (%)	Silt (%)	Fine sand (%)	pH	N (tonnes ha^{-1}) 0–50 cm	C:N 0–15 cm
CHR	8.1	600	13	18	46	7.7	7.7	10
ULB	7.5	881	2	2	31	4.6	4.4	33

Temp. and Prec.: Mean annual temperature and mean annual precipitation. Normal 1961–90. Interpolated from Danish Meteorological Institute climate stations by Finn Plauborg, Danish Institute of Agricultural Sciences.
Clay, silt and fine sand: Average subsoil texture (50–100 cm): clay <0.002 mm, silt 0.002–0.02 mm and fine sand 0.02–0.2 mm.
pH: Subsoil pH 50–100 cm measured in 0.01 M CaCl$_2$.
N, C:N: mineral soil pools, O horizon excluded. Total nitrogen by Kjeldahl digestion. Carbon determined by dry combustion.

only seldom by roots. Studies of primary mineral weathering, e.g. rock granules, when incubated by this technique in different forest types show that soil properties and tree species influence mineral transformations [7]. Trees influence soils by the architecture of crowns and roots, the chemistry of root exudates, the decomposability of litter, the soil fauna and other traits [6]. Soils influence trees through nutrient and water availability. Examples of soil–tree interactions have been shown in a Danish tree species trial established in 1964–65. Tree species planted in adjacent plots in 13 blocks across a soil gradient in Denmark from nutrient-poor sandy soils to nutrient-rich loamy soils influenced the pH in the forest floor [8] and the top mineral soil [9], Norway spruce (*Picea abies* (L.) Karst.) plots had higher concentrations of dissolved organic carbon in the forest floor than broadleaved plots [10], and biomass production was higher [11] and decomposition of the forest floor was faster on nutrient-rich loamy soils compared with nutrient-poor sandy soils [12]. These differences in forest floor properties due to tree species and soil type may influence the dissolution of wood ash when it is recycled to the forest. Here, the effect of environment with regard to tree species and soil type on the dissolution of granulated wood ash was examined by the investigation of chemical changes in the element composition of granulated wood ash incubated in mesh bags in the forest floor.

2. Materials and methods

A nutrient-poor (Ulborg) and a nutrient-rich (Christianssæde) site from the Danish tree species trial were selected for the study [13]. Even-aged neighbouring monoculture stands of beech (*Fagus sylvatica* L.), pedunculate oak (*Quercus robur* L.), Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) and Norway spruce were planted in 1964–65 at each site. The plots were not replicated within the site, making a total of eight plots in this investigation. Christianssæde (CHR) is located on the island Lolland (54°47′N, 11°22′E). The soil at CHR is an *oxyaquic Hapludalf* (World Reference Base: Orthicalcic Luvisol) developed on calcareous loamy till from the Weichsel glaciation. The soil classifications refer to the USDA soil taxonomy [14]. The soil contains 28% calcium carbonate, CaCO$_3$, from 73–110 cm soil depth. Ulborg
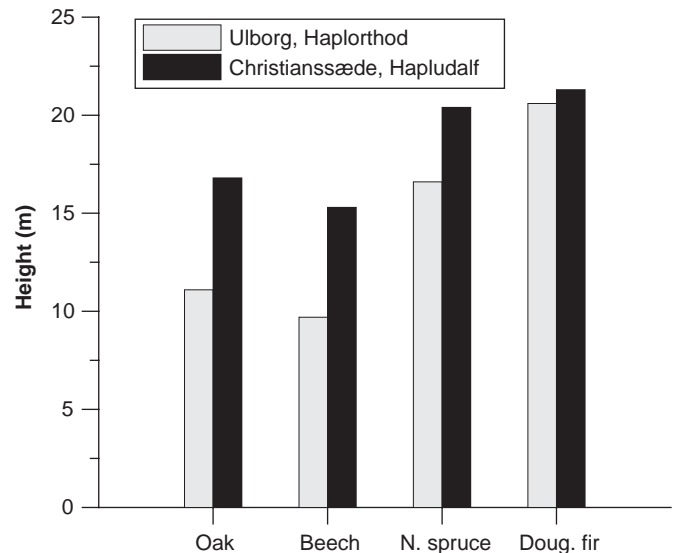

Fig. 1. Height (H_g), at mean tree diameter in 1998 at Ulborg and Christianssæde (Forest & Landscape Denmark, unpublished data).

(ULB) is located in western Jutland. The soil at ULB is a *Typic Haplorthod* [14] or a Haplic podzol (World Reference Base) developed from coarse sandy till deposited during the Saale glaciation. CHR is very nutrient rich in comparison to ULB as indicated by high nutrient pools, high subsoil pH and low C:N ratio in the top mineral soil in contrast to the sandy nutrient-poor podsolised ULB soil (Table 1). In 1998, stand heights (H_g) for the mean tree diameter in the four plots were 15.3–21.3 m at CHR at age 35–37 years from seed year and 8.3–16.2 m at ULB[1] at age 38 years from seed year (Fig. 1). Mesh bags, 5 cm by 10 cm, made of polyamide with mesh size 53 μm were filled with 10 g granulated wood ash. The wood ash granules were fly ash from a wood residue-fired circulating fluidised bed (CFB) boiler, Eskilstuna power plant, Sweden, that had been stabilised by granulation. The fly ash was mixed with water and cement in an ash:water:cement ratio of about 69:28:3.4, granulated, dried and sieved [15]. The ash pellets produced were used in similar experiments (e.g. [15,16]). In this experiment the 2–4 mm fraction was used. The mesh bags were placed in the top mineral soil at a depth of 5 cm

---

[1]B. Bilde-Jørgensen and V. Kvist-Johansen, Forest & Landscape Denmark, personal communication.

at CHR, where the O horizons are mostly very thin, and below the mor layer at ULB. Four bags were placed in each plot (tree stand) in September 1991 and recovered in June 1999, except three bags that were lost. The mean values from four bags from each plot were used in the statistical analyses. The mesh bags were dried at $105\,°C$, and the ash granules were recovered and weighed. A sample kept in dry storage during the incubation represented the control reference to the incubated samples. Loss on ignition (LOI), pH ($0.01\,M$ $CaCl_2$, sample:solute ratio 1:10) and cations extractable in ammonium nitrate ($1\,M$ NH_4NO_3 [17]) were analysed. For the analysis of total element contents, the ash samples were dissolved in hydrofluoric acid (HF). The elements calcium (Ca) magnesium (Mg), potassium (K), sodium (Na), aluminium (Al), manganese (Mn), iron (Fe), silicon (Si) and phosphorus (P) in the extracts were determined by ICP-AES.

2.1. Calculations and statistics

Element concentrations were based on the dry weight ($105\,°C$) of the sample. Percentage changes in mass and concentration were calculated on a dry weight basis. Concentration changes were calculated by deduction of the concentration of element x in sample i(year 7) from the initial concentration, $C_{x(\text{control})}/C_{x(\text{year 7})}$, using the control sample concentration as initial concentration of sample i. The ratio of salt-extractable elements to total element content was calculated. Changes in the mass of Ca, Mg, K, Na, Al, Mn, Fe, P and Si were calculated as (1)

$$W_{i(\text{initial})} \times C_{x(\text{control})}/W_{i(\text{year 7})} \times C_{xi(\text{year 7})}, \tag{1}$$

where $W_{i(\text{initial})}$ is the initial sample weight ($i = 1,\dots, 29$; should be $8 \times 4 = 32$, but three bags were lost during incubation), $C_{x(\text{control})}$ the concentration of element x in control sample, $W_{i(\text{year 7})}$ the sample weight of ash in bag i after incubation and $C_{xi(\text{year 7})}$ is the concentration of element x in bag i after incubation. x denotes the elements Ca, Mg, K, Na, Al, Mn, Fe, P or Si.

The sum of salt-extractable cations (CAT) was calculated as

$$\text{CAT} = \sum Ca^{2+}, Mg^{2+}, K^+, Na^+, Al^{3+}, Fe^{3+}, Mn^{2+}. \tag{2}$$

The changes in concentration and mass of elements were tested by Student's t-test assuming that the control sample was the true reference value. The effect of site ($N = 2$) and tree species ($N = 4$) on ash properties was tested by two-way ANOVA [18].

3. Results

3.1. Changes in element concentrations and pH

Recovery of the samples after destruction in hydrofluoric acid expressed as elements converted to oxides + LOI was 91% (std. dev. 5%), and the recovery of the control sample was 95%. The most abundant elements in the control sample were Si ($226.0\,\text{mg}\,\text{g}^{-1}$), Ca ($120.4\,\text{mg}\,\text{g}^{-1}$), Al ($47.7\,\text{mg}\,\text{g}^{-1}$), K ($39.6\,\text{mg}\,\text{g}^{-1}$), Fe ($14.0\,\text{mg}\,\text{g}^{-1}$), Mg ($13.9\,\text{mg}\,\text{g}^{-1}$), Na ($10.1\,\text{mg}\,\text{g}^{-1}$), P ($2.9\,\text{mg}\,\text{g}^{-1}$) and Mn ($0.7\,\text{mg}\,\text{g}^{-1}$). The LOI in the control sample was 10.9% (Table 2). These values are within the range of what is commonly found in wood ash. However, P concentrations were rather low [19].

There was no significant effect of tree species or site on mass loss, pH, LOI or CAT (data not shown). CAT decreased from $1407\,\text{mmol}_c\,\text{kg}^{-1}$ in the control to $789\,\text{mmol}_c\,\text{kg}^{-1}$ (CHR) and $822\,\text{mmol}_c\,\text{kg}^{-1}$ (ULB). Salt-extractable Al was not detectable in any of the samples and Fe was detected only in two samples in the Norway spruce plots (ULB $0.002\,\text{mg}\,\text{g}^{-1}$, CHR $0.002\,\text{mg}\,\text{g}^{-1}$). Salt-extractable Mn was significantly higher in Norway spruce plots ($0.07\,\text{mg}\,\text{g}^{-1}$) in comparison with beech ($0.05\,\text{mg}\,\text{g}^{-1}$) and oak plots ($0.04\,\text{mg}\,\text{g}^{-1}$), while Douglas-fir was in between ($0.06\,\text{mg}\,\text{g}^{-1}$). This was the only significant effect of tree species on salt-extractable elements.

Salt-extractable Mg was significantly higher at ULB ($0.6\,\text{mg}\,\text{g}^{-1}$) compared with CHR ($0.4\,\text{mg}\,\text{g}^{-1}$), which may be due to the high Mg deposition from the nearby North Sea [20].

Wood ash total element concentrations were not significantly affected by tree species. Thus, the four observations from each site were considered to be samples from the same population and unaffected by tree species. The initial pH of 7.6 (Table 2) in the treated ash indicates

Table 2
Means and standard deviations of properties of the ash granulates by site

Site	N	ML			pH			LOI			CAT		
		Mean (%)	Std.	t-test	Mean	Std.	t-test	Mean (%)	Std.	t-test	Mean ($\text{mmol}_c\,\text{kg}^{-1}$)	Std.	t-test
CHR	4	21.4	3.0	***	7.3	0.03	***	10.7	0.66	ns	789	18.2	***
ULB	4	18.9	0.4	***	7.3	0.005	***	11.1	0.09	*	822	15.7	***
Control	1	0			7.6			10.9			1407		

Student's t-test for rejection of the hypothesis: H_0: Identity with control sample.
* = $P<0.05$, ** = $P<0.01$, *** = $P<0.0001$. ns = not significant.
ML: Mass loss during incubation, %.
LOI: Loss on ignition after heating to $350\,°C$.
CAT: Salt-extractable ($1\,M$ NH_4NO_3) cations, $\sum Ca^{2+}$, Mg^{2+}, K^+, Na^+, Al^{3+}, Fe^{3+}, Mn^{2+}, $\text{mmol}_c\,\text{kg}^{-1}$.

that oxides and hydroxides had reacted with water and atmospheric carbon dioxide during granulation, since raw wood ash has an alkaline reaction with water in the range 9–13 [21]. pH in 0.01 M $CaCl_2$ extracts of the ash had declined to 7.3 on both sites, indicating that neutralisation processes continued during incubation but very slowly (Table 2).

3.2. Changes in extractable cation concentrations

A decline in the ratio of salt extractable to total element concentration (expressed as 'ext:tot' in Table 3) may indicate that the nutrients were not adsorbed to ash surfaces after they had been released from the minerals in the ash. Salt-extractable concentrations and total concentrations of Ca, Mg, K and P had declined significantly during incubation (Table 3). The salt-extractable Ca concentration had declined from 18.4 to 13.7 mg g^{-1}, while the total content had declined from 120.4 to 91.9 mg g^{-1} (CHR) and 98.3 mg g^{-1} (ULB). The ratio ext:tot was unchanged, 15% at CHR, but only slightly lower at ULB, 14%. Salt-extractable Mg declined from 1.6 to 0.4–0.6 mg g^{-1}; total element concentration of Mg declined from 13.9 to 11.1–11.3 mg g^{-1} and ext:tot declined from 11% to 4–6%. Salt-extractable K concentrations declined from 14.0 to 2.0 mg g^{-1} (CHR) and 2.5 mg g^{-1} (ULB). The ratio ext:tot for K declined from 35% to 7–8%, indicating a faster preferential K release. Total P concentrations were unchanged. The salt-extractable P was 9% of total P and decreased to 7% after incubation.

3.3. Mass changes

Tree species and site (soil type) did not influence the loss of nutrients after incubation (Table 4). On average, 19.8% of the wood ash mass was lost. At CHR, the losses of nutrient mass were 37.7% (Ca), 35.1% (Mg), 36.5% (K) and 17.8% (P), and at ULB they were 33.4% (Ca), 33.9% (Mg), 35.0% (K) and 19.2% (P). Actual mass losses may have been larger since matter might have entered the bags during incubation.

4. Discussion and conclusion

We measured the net release of nutrients from granulated wood ash after 7 years of incubation in forest soils. The dynamics of dissolution during the incubation, transformation of chemical compounds in the ash and possible influxes to the bags were not studied. A similar mesh bag study in Sweden using the same granulated ash showed that K release after 2 years of incubation was proportionally higher (approximately double: 20% K and 10% Ca) than the Ca and Mg release [16]. In our investigation, the loss of Ca, Mg and K was proportionally equal after 7 years, and approximately 35% of the initial content of Ca, Mg and K. It is most likely that a considerable amount of K from the ash was dissolved and leached together with sulphate and chloride as counterions within the first years. Such initial K leaching has been observed in other studies as well (e.g. [22]).

The reactivity of wood ash depends on the treatment of the ash prior to application in the forest. Stabilised ash

Table 3
Extractable (1 M NH_4NO_3) and total element concentrations, and ratio extractable:total for Ca, Mg, K and P after incubation from 1991 to 1999 at two sites under four tree species

	N	Extractable			Total			Ext/tot		
		Mean (mg g^{-1})	Std.	t-test	Mean (mg g^{-1})	Std.	t-test	Mean (%)	Std.	t-test
Ca										
CHR	4	13.7	0.11	***	91.9	10.4	*	15	2.0	NS
ULB	4	13.7	0.07	***	98.3	1.2	***	14	0.1	***
Control	1	18.4	–		120.4	–		15	–	–
Mg										
CHR	4	0.4	0.07	***	11.1	0.7	**	4	0.4	***
ULB	4	0.6	0.03	***	11.3	0.4	***	6	0.4	***
Control	1	1.6	–		13.9	–		11		
K										
CHR	4	2.0	0.35	***	31.9	0.7	***	7	1.1	***
ULB	4	2.5	0.24	***	31.7	0.8	***	8	0.9	***
Control	1	14.0	–		39.6	–		35		
P										
CHR	4	0.2	0.04	*	3.0	0.1	NS	7	1.4	*
ULB	4	0.2	0.03	*	2.9	0.2	NS	7	0.8	**
Control	1	0.3	–		2.9	–		9		

Estimates of means and standard deviations. Student's t-test within site: H_0: Identity with control sample. * = $P < 0.05$, ** = $P < 0.01$, *** = $P < 0.0001$. ns = not significant.

Table 4
Nutrient mass (g) of Ca, Mg, K and P before and after incubation from 1991 to 1999 at two sites, and decrease in percent of initial mass

	N	1991		1999		Change		Change	
		Mean (g)	Std.	Mean (g)	Std.	Mean (g)	Std.	Mean (%)	Std.
Ca									
CHR	4	1.21	0.005	0.75	0.10	0.46	0.10	38	8.6
ULB	4	1.21	0.007	0.81	0.07	0.40	0.06	33	5.4
Mg									
CHR	4	0.14	0.001	0.09	0.01	0.05	0.01	35	8.3
ULB	4	0.14	0.001	0.09	0.01	0.05	0.01	34	7.0
K									
CHR	4	0.40	0.002	0.25	0.01	0.15	0.01	37	3.3
ULB	4	0.40	0.002	0.26	0.01	0.14	0.01	35	2.6
P									
CHR	4	0.03	0.0001	0.02	0.001	0.01	0.001	18	4.1
ULB	4	0.03	0.0002	0.02	0.003	0.01	0.003	19	9.6

Estimate of means and standard deviations for four tree species.

Table 5
Nutrient release from ash pellets in $kg\,ha^{-1}\,y^{-1}$ incubation at two ash doses (normal and extreme dose) compared with soil nutrient pools, $kg\,ha^{-1}$, and estimated accumulation in woody biomass in Norway spruce and beech plots in the same period in $kg\,ha^{-1}\,y^{-1}$

	Ca	Mg	K	P
Soil pool, 0–100 cm	$(kg\,ha^{-1})$			
CHR	29042	789	660	2518
ULB	109	82	103	147
Nutrient release from ash granulates 1991–1999	$(kg\,ha^{-1}\,y^{-1})$			
Ash dose, 3 tonnes ha^{-1} granulates	19	2	6	0.2
Ash dose, 10 tonnes ha^{-1} granulates	65	7	21	0.8
Woody biomass accumulation 1990–1998	$(kg\,ha^{-1}\,y^{-1})$			
Norway spruce (stem biomass)				
CHR 30 $m^3\,ha^{-1}\,y^{-1}$	10.9	1.1	3.6	1.2
ULB 13 $m^3\,ha^{-1}\,y^{-1}$	3.6	0.6	1.7	0.2
Beech (total woody biomass)	$(kg\,ha^{-1}\,y^{-1})$			
CHR 17 $m^3\,ha^{-1}\,y^{-1}$	10.1	3.2	10.7	1.3
ULB 8.2 $m^3\,ha^{-1}\,y^{-1}$	4.8	1.5	5.1	0.6

Biomass accumulation based on calculated volume growth (Bruno Bilde Jørgensen and Vivian Kvist Johannsen, Forest & Landscape Denmark, personal communication), and stem wood nutrient concentrations in Norway spruce at sites Ulborg (P 0.05, K 0.4, Ca 0.8, Mg 0.14 $g\,kg^{-1}$) and Frederiksborg (P 0.11, K 0.3, Ca 1.0, Mg 0.10 $g\,kg^{-1}$ [25]) and beech (P 0.13, K 1.07, Ca 1.01, Mg 0.32 $g\,kg^{-1}$ [26]). Wood density Norway spruce 370 kg dry matter per m^3 fresh stemwood and beech: 580 kg dry matter per m^3 fresh stemwood.
Nutrients: Ca, Mg, K and P pools: calculated from concentration, bulk density and depth of soil horizons. Ca, Mg and K: exchangeable in NH_4-Ac at pH 7. P: extractable in 0.1 M H_2SO_4.

granulates are less reactive than raw wood ash [19]. After the incubation, the amount of salt-extractable exchangeable cations decreased, perhaps indicating dissolution of salt in the ash yielding a decreased reactivity of the surface of the ash particles. Further, the proportion of extractable cations to the corresponding total element content decreased, indicating that the cations were not sorbed to the surface of the ash granulates. The decline in salt-extractable cation concentrations could also indicate that fewer sorption sites were available following the incubation. Even with application of raw wood ash in standard doses of 2–3 tonnes ha^{-1}, leaching of base cations is sparse

[19]. The use of stabilised, granulated ash should thus pose a lower risk of nutrient leaching caused by a fast dissolution of salts than the application of untreated ash.

A calculation of release from ash versus accumulation in woody aboveground biomass may illustrate this: the release of nutrients from ash granulates on a hectare basis for two doses of ash, 3 and 10 tonnes ha^{-1}, was calculated. We assumed that foliage biomass was constant from age 26 to 34 years after planting (Table 5). The annual release was compared with tree accumulation in woody biomass in Norway spruce and beech during the incubation period and the available mineral soil nutrient pools (Table 5). We

stress that the estimate of nutrient release from the ash granulates is very conservative (low) due to the protective function of the mesh bags and the close contact between granulates within the mesh bags affecting the chemical properties around the pellets. Nutrient accumulation in woody biomass was approximately two times higher at CHR than at ULB for both species due to higher biomass increment at CHR. Within site, accumulation of Ca and P was comparable for both species, whereas accumulation of Mg and K was two to three times higher in beech. Nutrient release from an ash dose of $3\,\mathrm{tonnes\,ha^{-1}}$ and biomass accumulation during the incubation were negligible in comparison with available soil nutrient pools at CHR even if the dissolution were total and not only 35% (19% for P) nutrient loss.

At ULB, the soil pools of nutrients are very low. The humus layer holds a sizeable nutrient store, which was not included in our estimates that focused on the mineral soil. Nutrient release from the ash could compensate nutrient accumulation in aboveground woody biomass at ULB, except for P. The ash granulates had a rather low P concentration, $2.9\,\mathrm{mg\,g^{-1}}$, in comparison with most wood ashes [19], and even the total dissolution of $3\,\mathrm{tonnes\,ha^{-1}}$ of granules (100% versus 19% mass loss) would not result in sufficient release of P to compensate the calculated aboveground woody accumulation during the incubation period (Table 5).

This is an ecosystem mass balance approach that does not reflect whether nutrients applied to the surface are immobilised by the trees. The mineral bags were penetrated by mycorrhizal roots that were attached to the surface of granulates, most abundantly at the nutrient-poor ULB site [23]. Other soil organisms may have been excluded from the bags due to the fabric used. The small mesh size may be a barrier protecting the granules from decomposition. That trees can access fertilisers applied to the forest floor is demonstrated in many fertiliser experiments [24]. The ash application in the bags equalled a plot treatment of $20\,\mathrm{tonnes\,ha^{-1}}$ ash pellets when scaling up from the mesh bag area of $50\,\mathrm{cm^2}$. However, the aim of the study was not to investigate the effect of such an extreme application rate. This local concentration of nutrients in applied ash pellets may have introduced an artefact, increasing the mycorrhiza colonisation of the bags and thus enhancing the removal of nutrients. Likewise the physical (less dynamic wetting/drying cycles) and chemical environment (less external acidity) in the bags are likely to have differed from even application of realistic ash doses (about 2–3 tonnes).

Application of stabilised ash may be a way to secure closed nutrient cycles in utilisation of forests while minimising the risks for negative impacts on ground vegetation and water quality. In comparison with potential nutrient losses following slash burning or rapid nutrient leaching from slash biomass, harvesting for energy production and recycling of ash may be a good alternative. The ash tested in this experiment showed a very slow and

equal dissolution rate across the range of physical and chemical environments found at the two sites. The ash was mixed with a small amount of cement as a pre-treatment. This may contribute to explaining the very slow dissolution rate. Other types of pre-treated wood ash may be less resistant [2]. In contrast to our hypothesis, the dissolution of the granulated wood ash was unaffected by different physical and chemical environments formed by tree species and soil type. This may be caused by the stability of the ash granulates and the mesh bag incubation method. The environment inside the mesh bag and the close contact between granulates was probably not comparable with the more aggressive weathering environment for unprotected granulates in the forest floor. However, for practical application of the results, the sensitivity of pellets to dissolution under different tree species is of minor importance. The stable response of the pellets in these humid temperate forest types and the controlled release of nutrients to compensate for harvested nutrients are important features for practical application of the results.

We conclude that the stabilised ash is robust in the environment. At nutrient-poor sites such as ULB, available soil nutrient pools are low and ash recycling may be a vital part of long-term nutrient sustainability at the site if biomass is harvested.

Acknowledgements

References

[1] Steenari BM, Karlsson LG, Lindqvist O. Evaluation of the leaching characteristics of wood ash and the influence of ash agglomeration. Biomass & Bioenergy 1999;16(2):119–36.

[2] Ring E, Lövgren L, Nohrstedt H-Ö, Jansson G. Ash fertilisation in a clearcut and in a Scots pine stand in Central Sweden-effects on soil-water and soil chemistry coupled to laboratory leachings of six ash products. In: Frumerie G, editor. Oskarshamn, Skogforsk, The Forestry Research Institute of Sweden. 1999. vol. 2. p. 1–51.

[3] Raulund-Rasmussen K, Borggaard OK, Hansen HCB, Olsson M. Effects of natural organic solutes on weathering rates of soil minerals. European Journal of Soil Science 1998;49:397–406.

[4] Robarge WP. Minerals, solubility of encyclopedia of soil science. New York, NY: Marcel Dekker, Inc.; 2003.

[5] Augusto L, Bonnaud P, Ranger J. Impact of tree species on forest soil acidification. Forest Ecology and Management 1998;105:67–78.

[6] Binkley D, Giardina C. Why do tree species affect soils? The warp and woof of tree–soil interactions. Biogeochemistry 1998;42:89–106.

[7] Augusto L, Turpault MP, Ranger J. Impact of forest tree species on feldspar weathering rates. Geoderma 2000;96(3):215–37.

[8] Vesterdal L, Raulund-Rasmussen K. Forest floor chemistry under seven tree species along a soil fertility gradient. Canadian Journal of Forest Research 1998;28:1636–47.

[9] Raulund-Rasmussen K, Vejre H. Effect of tree species and soil properties on nutrient immobilization in the forest floor. Plant and Soil 1995;168–69:345–52.

[10] Strobel BW, Hansen HCB, Borggaard OK, Andersen MK, Raulund-Rasmussen K. Composition and reactivity of DOC in forest floor soil solutions in relation to tree species and soil type. Biogeochemistry 2001;56(1):1–26.

[11] Callesen I, Raulund-Rasmussen K, Jørgensen BB, Johannsen VK. Growth of beech, oak, and four conifer species along a soil fertility gradient. Baltic Forestry 2006;12(1):14–23.

[12] Vesterdal L. Influence of soil type on mass loss and nutrient release from decomposing foliage litter of beech and Norway spruce. Canadian Journal of Forest Research 1999;29(1):95–105.

[13] Holmsgaard E, Bang C. Et træartsforsøg med nåletræer, bøg og eg; de første 10 år. (A species trial with conifers, beech and oak; the first ten years). Det Forstlige Forsøgsvæsen, Danmark 1977;35:159–96 [in Danish].

[14] Soil Survey Staff USDA. Keys to soil taxonomy. 8th ed. Blacksburg, VA: Pocahontas Press, Inc.; 1998.

[15] Eriksson HM. Short-term effects of granulated wood ash on forest soil chemistry in SW and NE Sweden. Scandinavian Journal of Forest Research 1998:43–55.

[16] El Make M. Base cations in relation to weathering of phyllosilicates and forest management in Swedish forest ecosystems. PhD Thesis, Swedish University of Agricultural Sciences, 2000.

[17] Stuanes AO, Ogner G, Opem M. Ammonium nitrate as extrant for soil exchangeable cations, exchangeable acidity and aluminium. Communications in Soil Science and Plant Analysis 1984;15:773–8.

[18] SAS institute. SAS User's Guide: Statistics Version 6. 4th ed. Cary, NC, USA: SAS Institute Inc.; 1990.

[19] Karltun E, Saarsalmi A, Ingerslev M, Mandre M, Gaitnieks T, Varnagyrite I. Wood ash recycling. In: Röser D, Asikainen A, Raulund-Rasmussen K, Stupak I, editors. Sustainable use of forest biomass for energy. A synthesis with focus on the Nordic and Baltic Region. Managing forest ecosystems, vol. 12. Berlin: Springer; 2007, ISBN 978-1-4020-5053-4 [submitted for publication].

[20] Hovmand MF, Bille-Hansen J. Atmospheric input to Danish spruce forests and effects on soil acidification and forest growth based on 12 years measurements. Water Air and Soil Pollution 1999;116:75–88.

[21] Demeyer A, Nkana JCV, Verloo MG. Characteristics of wood ash and influence on soil properties and nutrient uptake: an overview. Bioresource Technology 2001;77(3):287–95.

[22] Rumpf S, Ludwig B, Mindrup M. Effect of wood ash on soil chemistry of a pine stand in Northern Germany. Journal of Plant Nutrition and Soil Science-Zeitschrift fur Pflanzenernahrung und Bodenkunde 2001;164(5):569–75.

[23] Ravn-Jonsen LJ. Sammenhæng mellem træart, forvitringsmiljø og mængden af mycorrhiza-hyfer [BSc Report]. Frederiksberg: Institute of Ecology, the Royal Veterinary and Agricultural University; 2001 [in Danish].

[24] Ingerslev M, Malkonen E, Nilsen P, Nohrstedt HO, Oskarsson H, Raulund-Rasmussen K. Main findings and future challenges in forest nutritional research and management in the Nordic countries. Scandinavian Journal of Forest Research 2001;16(6):488–501.

[25] Møller IS, og Ingerslev M. ESBEN-et EXCEL-program til estimering af biomasse- og næringsstofudtag ved udnyttelse af heltræer i rødgran. Videnblade Skovbrug 8.5-16. 2001. [In Danish].

[26] Hagen-Thorn A, Armolaitis K, Callesen I, Stjernquist I. Macronutrients in tree stems and foliage: a comparative study of 6 temperate forest species planted at the same sites. Annals of Forest Science 2004;61:489–98.