ACTA UNIVERSITATIS AGRICULTURAE SUECIAE

SILVESTRIA 208

Wood Ash Application
Effects on elemental turnover in a cutover peatland and uptake in vegetation

Torbjörn Nilsson

SWEDISH UNIVERSITY OF AGRICULTURAL SCIENCES

Wood ash application - effects on elemental turnover in a cutover peatland and uptake in vegetation

Torbjörn Nilsson

Akademisk avhandling som för vinnande av filosofie doktorsexamen kommer att offentligen försvaras i sal 1, Arrheniusplan 8, Inst. för kemi, SLU, Uppsala, torsdagen den 22 november 2001, kl. 09.30.

Abstract

Forest harvesting and removal of logging residues implies loss of essential soil nutrients and may in the long-term endanger site productivity. Compensatory fertilization is now recommended in Sweden for such sites. As wood ash contains all the mineral elements that were withdrawn from the forest ecosystem by harvest, the ash is often suitable as a compensatory fertilizer. Peat is also a fuel that is used to some extent in Sweden. After peat harvesting is terminated, the cutover peatland should be reclaimed. The most common re-use of cutover peatlands is forestry. However, as the nutrient pool in the remaining peat is usually low, especially for P and K, nutrients need to be applied to establish and maintain a sustainable biomass production. As wood ash contain the most necessary nutrients, it is a suitable fertilizer for forestry on cutover peatlands. This thesis investigates how wood ash fertilization on a cutover peatland affects i) the distribution of ash elements in the peat, ii) the leaching of these ash elements and iii) the biomass and nutrient allocation in different compartments in 3-7 year-old trees of seven different species; and how the application of different wood ash and lime products on a mineral soil affects iv) the uptake of nutrients and heavy metals in bilberry fruit.

To achieve soil nutrient conditions suitable for forest growth, wood ash (23 000 kg ha^{-1}) was applied to a cutover peatland in west-central Sweden. Seven tree species were planted and for all of these except two Salix species, the increase in soil pH and nutrient pools seemed sufficient to maintain a sustainable biomass production. The crucial growth limiting nutrients, K and P, were applied in large quantities, 670 and 210 kg ha^{-1} respectively. However, these two elements will probably be growth limiting in the next tree generation, as an marked increase in the output of K was observed in the stream water, and as phosphate ions could be adsorbed to the large amount of Fe compounds present in the peat.

In the short-term, the application of different wood ash products on a mineral soil did not significantly affect the content of different nutrients or heavy metals in bilberry fruit, even if high doses were applied.

It can be concluded that wood ash fertilization on cutover peatlands and compensatory fertilization with wood ash on mineral soils are both suitable soil improvement measures that have relatively small effects on the environment if precautions are taken concerning the quality of the wood ash product.

Key words: Alnus incana, Alnus glutinosa, base cations, *Betula pubescens,* heavy metals, leaching, *Picea abies, Pinus sylvestris, Salix dasyclados, Salix viminalis, Vaccinium myrtillus*

Distribution:
Swedish University of Agricultural Sciences
Department of Forest Soils
SE-750 07 UPPSALA, Sweden

Uppsala 2001
ISSN 1401-6230
ISBN 91-576-6092-1

Wood Ash Application
Effects on elemental turnover in a cutover peatland and uptake in vegetation

Torbjörn Nilsson
Department of Forest Soils
Uppsala

Doctoral thesis
Swedish University of Agricultural Sciences
Uppsala 2001

Acta Universitatis Agriculturae Sueciae
Silvestria 208

ISSN 1401-6230
ISBN 91-576-6092-1

Tryck: SLU Service/Repro, Uppsala 2001

Abstract

Nilsson, T. 2001. *Wood ash application - effects on elemental turnover in a cutover peatland and uptake in vegetation.* Doctor's dissertation.
ISSN 1401-6230 , ISBN 91-576-6092-1.

Forest harvesting and removal of logging residues implies loss of essential soil nutrients and may in the long-term endanger site productivity. Compensatory fertilization is now recommended in Sweden for such sites. As wood ash contains all the mineral elements that were withdrawn from the forest ecosystem by harvest, the ash is often suitable as a compensatory fertilizer. Peat is also a fuel that is used to some extent in Sweden. After peat harvesting is terminated, the cutover peatland should be reclaimed. The most common re-use of cutover peatlands is forestry. However, as the nutrient pool in the remaining peat is usually low, especially for P and K, nutrients need to be applied to establish and maintain a sustainable biomass production. As wood ash contain the most necessary nutrients, it is a suitable fertilizer for forestry on cutover peatlands. This thesis investigates how wood ash fertilization on a cutover peatland affects i) the distribution of ash elements in the peat, ii) the leaching of these ash elements and iii) the biomass and nutrient allocation in different compartments in 3-7 year-old trees of seven different species; and how the application of different wood ash and lime products on a mineral soil affects iv) the uptake of nutrients and heavy metals in bilberry fruit.

To achieve soil nutrient conditions suitable for forest growth, wood ash (23 000 kg ha^{-1}) was applied to a cutover peatland in west-central Sweden. Seven tree species were planted and for all of these except two Salix species, the increase in soil pH and nutrient pools seemed sufficient to maintain a sustainable biomass production. The crucial growth limiting nutrients, K and P, were applied in large quantities, 670 and 210 kg ha^{-1} respectively. However, these two elements will probably be growth limiting in the next tree generation, as an marked increase in the output of K was observed in the stream water, and as phosphate ions could be adsorbed to the large amount of Fe compounds present in the peat.

In the short-term, the application of different wood ash products on a mineral soil did not significantly affect the content of different nutrients or heavy metals in bilberry fruit, even if high doses were applied.

It can be concluded that wood ash fertilization on cutover peatlands and compensatory fertilization with wood ash on mineral soils are both suitable soil improvement measures that have relatively small effects on the environment if precautions are taken concerning the quality of the wood ash product.

Key words: Alnus incana, Alnus glutinosa, base cations, *Betula pubescens*, heavy metals, leaching, *Picea abies, Pinus sylvestris, Salix dasyclados, Salix viminalis, Vaccinium myrtillus*

Author's address: Torbjörn Nilsson, Department of Forest Soils, Swedish University of Agricultural Sciences, Box 7001, SE-750 07 UPPSALA, Sweden.
E-mail: Torbjorn.Nilsson@sml.slu.se

Contents

Introduction, 7
Background, 7
  Oil crisis and bioenergy, 7
  Peat harvesting, 8
  After-use alternatives for peat harvesting areas, 9
  Wood fuels and nutrient balance, 11
  Wood ash composition, 12
  Wood ash fertilization on peatlands, 13
  Wood ash application on mineral soils, 14

Objectives, 15

Study sites, 16

Results and discussion, 18
Effects of wood ash fertilization on cutover peatlands, 18
  Effects on field layer vegetation, 18
  Translocation within the peat and leaching of elements (Paper I and III), 19
  Plant uptake and tree growth (Paper II), 20
Potassium budget after wood ash fertilization on a cutover peatland, 21
  Transfers of K, 22
  Soil K pool, 23
  Input/output budget, 23
Uptake of elements in bilberry fruit (Paper IV), 24

Conclusions, 24

References, 25

Acknowledgements, 33

Appendix

Papers I-IV

The present thesis is based on the following papers, which are referred to by their Roman numerals:

I. Nilsson, T. and Lundin, L. 1996. Effects of drainage and wood ash fertilization on water chemistry at a cutover peatland. Hydrobiologia 335: 3-18.

II. Nilsson, T. Biomass production and nutrient uptake of young conifer and deciduous trees after fertilization with wood ash or lime on a cutover peatland. (Manuscript).

III. Nilsson, T. Vertical distribution of elements in a cutover peatland 1-4 years after wood ash fertilization. (Manuscript).

IV. Nilsson, T. & Eriksson, H.M. Elemental concentrations in the fruit of bilberry (*Vaccinium myrtillus* L.) after wood ash application. (Manuscript).

Paper I is reprinted with kind permission from Kluwer Academic Publishers.

Introduction

The harvesting of peat for fuel or horticultural purposes can usually only proceed for 20 - 100 years on a peatland site. When peat harvesting is terminated, the cutover peat area has to be reclaimed in one way or another. One after-use alternative for cutover peatlands is to afforest the site. However, the remaining peat at a harvested area is usually very poor in plant nutrients, especially P and K, as well as with low biological activity. Consequently the site must be treated with some type of fertilizer to achieve a sustainable forest growth.

The increased use of bioenergy in Sweden and other countries has also led to increased production of biofuel ash, peat ash and other waste products such as green liquor sludge, lime mud etc. These ashes and waste products can be looked upon as disposal problems or as lime products, fertilizers or soil amenders in agriculture or forestry. In Sweden, the National Forestry Board and the Environmental Protection Agency issued a policy in 1994 stating that wood ash from forests should be recycled to the forest. Effects of such wood ash recycling have been studied since the end of the 1980s in Sweden.

Background

Oil crisis and bioenergy

The oil crises in 1973/1974 caused an increase in research on, and use of, domestic energy sources in many countries. An increased understanding of the negative effects of fossil fuels has also led to an aspiration to use renewable energy sources. Different geographical and climatic conditions mean that there is a reliance on varying domestic energy sources, and sometimes also renewable energy sources, in different parts of the world.

In Sweden, crude oil and oil products accounted for 77 % of the total energy supply in 1970. The substantial increase in crude oil prices in late autumn 1973 consequently affected the Swedish economy very badly. The energy policy had to be changed drastically and large investments were made in nuclear power plants. The energy supply from crude oil and oil products decreased from 350 TWh in 1970 to about 210 TWh in the middle of 1980s, while nuclear power increased from zero to about 70 TWh. Today, 15 years later, the energy supply from these two energy carriers is about the same (Anon., 2000a). A referendum in 1980 led to a decision that the nuclear power plants in Sweden should sooner or later be shut down. As a consequence of this, environmental and energy policies in Sweden during the last 20 years have aimed to increase the use of domestic renewable energy sources and to replace as much as possible of the imported fossil fuels and the nuclear energy with domestic bioenergy[1] carriers.

A lot of research about renewable energy resources was begun in Sweden after the oil crisis. Biofuels and peat soon appeared to be the energy carriers that could make up the main part of renewable energy supply in Sweden. Since the 1980s many bioenergy systems, especially district heating plants, have also been developed. Before the oil crisis, nearly 100% of the fuel input for district heating plants was in the form of oil. In 1999, biofuels and peat accounted for over 50% of this input, while the portion of oil was only 10% (Anon., 2000a). The use of biofuels has also increased in the industry. As a consequence, the supply of biofuels and peat has increased from 43 TWh in 1970 to almost 94 TWh in 1999, or from less than 10% of the total energy supply in 1970 to almost 20% in 1999 (Anon., 2000a).

Peat harvesting

Peatlands belong to the world's least exploited terrestrial habitats. Nevertheless, they have experienced large losses in the past few centuries. Europe has, for example, lost 60% of its original 530 000 km^2 of peatland. These losses are primarily attributable to agriculture (50%), forestry (30%) and peat extraction (10%) (Joosten, 1997).

About 6.4 million hectares or 15% of Sweden's total land area is covered by a peat layer that is more than 30 cm thick. A further 3.7 million hectares of the land area are covered by a thin peat layer, less than 30 cm thick. Consequently, about 25% or 10 million hectares of the total land area is covered by a layer of peat of varying thickness. More than 1.5 million hectares have been drained for forestry and 0.6 million hectares drained for agricultural purposes (Hånell, 1989).

Already in the 19th century, peat was used in Sweden as fuel and litter. In the years between the two world wars, the production of peat litter reached a peak, but nowadays it is rather low. The production of peat for horticultural purposes increased in the second part of the 20th century and is at present about 1 million m^3 (Fredriksson, 1996; Anon., 2000b). During the two world wars production of energy peat peaked, but decreased during the 1950s and stopped totally at the end of 1960s. After the oil crisis in the seventies, the Swedish government gave support to the production of domestic fuels such as wood and peat and in 1980 the

---

[1] The term bioenergy is often defined as renewable energy produced from organic matter. This means that many energy carriers can be included in the term bioenergy; wood fuels (logs, bark, chips and energy forest), black liquor in pulp mills, peat, straw and energy grasses and refuse. The term biofuel is often used as a synonym for bioenergy, but in Sweden peat is usually not included in the term biofuel.

production of energy peat started again in Sweden. From a small scale in 1980, the production of fuel peat increased to more than 3 million m^3 in 1988. Since then, production has remained rather stable at around 3 million m^3, except for some wet and cold summers. In 1999, 2.65 million m^3 of fuel peat and 1.46 million m^3 of horticultural peat was harvested in Sweden. The amount of fuel peat, which was used mainly for production of hot water in district heating plants, corresponded to an energy supply of 2.8 TWh (Anon., 2000b).

In 2000, peat was harvested on 10 400 hectares for energy purposes in Sweden (Anon., 2001b). On 85% of that area, the peat is harvested by the sod peat method, and on the remaining area the peat is harvested by the milling method. Peat for horticultural purposes is harvested on approximately 500 hectares (Fredriksson, 1996). By 1999, concessions for fuel peat harvesting had been granted for 45 900 hectares. Larsson (1982) estimated that the potential peatland area available for large scale energy peat production was 350 000 hectares, corresponding to 5.5% of the peat areas in Sweden with more than 30 cm peat depth.

After about 20-50 years of peat harvesting, the remaining peat layer is usually so shallow and of such bad quality (high ash content) that peat harvesting must cease. According to information from Swedish peat producers in 1999, about 70 hectares of cutover peat had been reclaimed and peat harvesting had recently been terminated on approximately 160 hectares (Anon., 2000b).

After-use alternatives for peat harvesting areas

The total global peatland area previously and currently used by the peat industry can be estimated at 2.5-4 million hectares according to figures from Lappalainen (1996) and Kreshtapova et al. (2000). According to Nyrönen (1995) the area being used for harvest was 252 000 hectares in 1994. Large peat harvesting areas have consequently been terminated during the 20th century and peat harvesting will cease on more than 150 000 hectares currently being used in Ireland and Finland alone within the next 30 years (Selin & Nyrönen, 1998; Rowlands & Feehan, 2000). Peat harvest often results in the creation of large fields that are almost totally devoid of vegetation, even many years after exploitation has ceased.

The increased interest and awareness of the importance of wetland ecosystem conservation for water, carbon and nutrient cycles and for biodiversity have also led to increased efforts to conserve natural intact peatlands, but also to restore or reclaim peatlands used for agricultural, forestry, industrial or other purposes. In some countries, such as Germany, The Netherlands and Great Britain where bogs have become rare, the restoration of bogs has become a central practice in nature conservation (Wheeler & Shaw, 1995). In most of the countries where peat harvesting occurs, laws or regulations nowadays also exist which state that cutaway peat areas must be restored or reclaimed in one way or another.

While peatland restoration can be defined as "the managed restoration of harvested peatlands to their original wetland vegetation and functional wetland status", peatland reclamation can be defined as "the management of harvested peatlands to achieve a beneficial end use, often with the potential for economic return" (Malterer & Johnson, 1998). Restoration of peatlands is usually restricted to regeneration of fens or *Sphagnum* bogs, or construction of lakes and wetlands suitable as bird sanctuaries, fish ponds or water reservoirs (Nick, 1984; Eggelsmann, 1988; Havelka, 1988; Selin, 1996; Vasander & Roderfeld, 1996; Vikberg, 1996). Reclamation of peat cutover areas can include several land use alternatives; *e.g.* agriculture (crops, grassland), horticulture (berries, herbs, medicinal plants, flower seeds), but the most common land use so far is forestry (Podzharov, 1983; Stenbeck, 1985; Ferda, 1975, 1986; Krasilnikova et al., 1986; Valk, 1986; Selin, 1996; Kaunisto & Aro, 1996; Virkajärvi & Huhta, 1996; Gradeckas et al., 1998; Åman et al., 1998; Kukkonen et al., 1999; Uosukainen & Åman, 1999; Vestberg, 1999). However, the suitable land use of a cutover peatland depends on several criteria, such as topography, hydrology, geology, climate, and land ownership (Åman et al., 1998). Sometimes the wetland conservation policy overshadows these criteria.

Afforestation of cutover peatland areas

The most common re-use of cutover peatlands in Finland and Sweden is conventional forestry. Scots pine (*Pinus sylvestris* L.), downy birch (*Betula pubescens* Erh.) and silver birch (*Betula pendula* Roth.) are the most common species grown in cutover peatlands (Kaunisto & Aro, 1996). Short-rotations plantations, mainly willows (*Salix* spp.), have also been established on cutover peatlands (Nilsson et al., 1987; Olsson, 1990; Hytönen, 1995b).

A main prerequisite, especially for willows, is that the nutrient status in the remaining peat and the drainage conditions are regulated. In natural or drained peatlands, the highest concentrations of P and K are found in the 0-10 cm surface peat layer. The concentrations of P and K are considerably lower below this layer and usually stay at a very low level downwards in the peat profile. Some 10-20 cm above the mineral soil material, the P and K concentrations increase again. As the remaining peat layer after peat harvesting is usually less than 1 m deep, the amount of P and K in the remaining peat is often very low. Consequently, it is hazardous to establish tree plantations on cutover peatlands, without applying PK-fertilizers.

The soil pH in the remaining peat is usually below 5 and often below 4. As the fast-growing willow species have a high demand for nutrients and an optimum soil pH between 5.5 to 6.5, a willow plantation on a cutover area must be preceded by thorough soil amelioration measures (liming, fertilization, rotovation). Peat cutover areas are also exposed to late spring and summer frosts as these areas are located at lower elevations than the surroundings. Furthermore, the mineralization of the organic matter is usually low, mainly as a consequence of small populations of micro-organisms and soil animals in the remaining peat (Dooley & Dickinson, 1971; Ferda, 1975). Establishing tree plantations on cutover peatlands consequently necessitates comprehensive fertilization, but sometimes also other treatments such as complementary drainage and rotovation.

Fertilization of conventional forestry tree species on peatlands usually implies that PK- or NPK-fertilizers are used (Paavilainen and Päivänen, 1995). Fertilization with PK is generally sufficient in relatively nitrogen-rich sites, while nutrient-poor sites also need N to increase tree growth (Holmen, 1969; Kaunisto and Päivänen, 1985; Paavilainen and Päivänen, 1995). Trees growing on peatlands receiving low amounts of B via deposition may exhibit growth disturbances due to B deficiency (Bкруkke, 1979; Kolari, 1983) and consequently may require a fertilizer containing B. As deficiencies of P, K and micronutrients are usually pronounced on cutover peatlands, these sites need a more comprehensive supply of nutrients than PK- or NPK-fertilizers can provide. Furthermore, soil pH must often be raised on cutover peatlands before afforestation, especially if short-rotation plantations are to be established. Consequently, liming agents also often have to be applied. Fuel ashes are examples of possible fertilizers on cutover peatlands, as these ashes often contain all the important nutrients (except N) needed for tree growth and in addition have an alkalising effect. However, coal and oil ashes usually also have high contents of heavy metals and are therefore often not suitable as fertilizers. Biofuel ashes, on the other hand, generally have lower contents of heavy metals than coal and oil ashes.

Wood fuels and nutrient balance

The use of wood fuels (logs, bark, chips and energy forest) implies that wood biomass has been taken away from different sites in the forest. This biomass harvest also causes an export of nutrients from the site. Whole-tree harvesting (WTH), which involves the removal of logging residues, increases the export of nutrients. Swedish investigations have shown that WTH may decrease the pH value in the humus layer by up to 0.4 pH units, compared to conventional harvesting (CH) (Nykvist and Rosén, 1985; Staaf and Olsson, 1991; Egnell et al., 1998). This pH difference may persist for up to 20 years after harvest (Nykvist and Rosén, 1985). The soil pool of base cations and the base saturation usually also decrease after WTH (Olsson et al., 1996; Egnell et al., 1998) and a theoretical model showed that weathering would not compensate for the losses of base cations through WTH on most forest sites in Sweden (Olsson et al., 1993). Consequently, the harvesting of logging residues may endanger the long-term site productivity. Small reductions in tree volume growth on WTH sites in Sweden have also been observed, but these growth reductions are usually temporary

(Egnell et al., 1998). A series of field experiments in Finland, Norway and Sweden indicated that WTH in thinnings of Scots pine and Norway spruce stands would result in a production loss, averaging 5-6%, during the first 10-year period. This production loss was thus probably an effect of reduced N supply (Jacobson et al., 2000). However, as there is a risk of negative base cation balance after WTH, the National Forestry Board in Sweden has recommended that compensatory fertilization should be done after WTH (Anon., 2001a). Several compensatory fertilizers may be used, but in Sweden wood ash is often used as it has a comprehensive composition of base cations, phosphorus and micronutrients. Applying wood ash to forest soils can also be looked upon as a recycling of elements removed from the forest during harvest.

Wood ash composition

Combustion of biofuels occurs at district heating plants, forest industries (paper mills, sawmills) or in single house boilers. Different kinds of ash are produced depending on the type of fuel and the combustion technique used. Among the biofuel ashes annually produced in Sweden, wood ash constitutes the largest quantity, about 200 000 tonnes. These large volumes were formerly, and to some extent still, looked upon as a solid waste disposal problem. Consequently, almost all of this annually produced amount of wood ash was, and still is, deposited in landfills. As wood fuels are often co-combusted with other fuels, such as peat, coal, oil, and refuse, these ashes are often polluted with heavy metals and organic contaminants and are consequently not suitable for application on forest soils. The present amount of wood ash that can be recycled annually to Swedish forests is calculated to be about 50 000 tonnes (dry matter) (Lindkvist, 2000).

Compared to peat ash and coal ash, wood ash usually has higher contents of P, K, Ca, Mg and Mn and a lower content of heavy metals (Table 1). As wood ash is a highly alkaline material with pH-values and lime effects that normally range from pH 11-13 and 20-45 % of CaO respectively (Lerner & Utzinger, 1986; Campbell, 1990; Eriksson, 1992; Muse & Mitchell, 1995; Someshwar, 1996; Mitchell & Black, 1997; Obernberger et al., 1997), it has been evaluated as a liming agent in agriculture (Lerner & Utzinger, 1986; Naylor & Schmidt, 1986, 1989; Ohno & Erich, 1990; Etiegni et al., 1991; Saarela, 1991; Clapham & Zibilske, 1992; Huang et al., 1992; Muse & Mitchell, 1995). Wood ash has also been tested in agriculture as a source of K, P and micronutrients (Naylor & Schmidt, 1989; Ohno & Erich, 1990; Saarela, 1991; Huang et al., 1992; Ohno, 1992; Krejsl & Scanlon, 1996; Mitchell & Black, 1997; Meyers & Kopecky, 1998; Voundi Nkana et al., 1998). In some studies wood ash has also been used as an amendment in municipal sludge, yard waste and pulp and paper composting operations (Logsdon, 1989; Campbell et al., 1995, 1997; Carpenter & Beecher, 1997; Hackett et al., 1999).

Table 1. Concentration ranges for selected major and minor elements in fly ashes from combustion of wood, peat and coal. Data from Nilsson and Timm (1983), Kofman (1987), Eary et al. (1990), Mattigod et al. (1990), Saarela (1991), Eriksson (1992), Misra et al. (1993), Pohlandt & Marutzky (1993), Veijalainen et al. (1993), Greger et al. (1995), Muse and Mitchell (1995), Someshwar (1996), Tammela et al. (1996), Vance (1996), Obernberger et al. (1997), Steenari and Lindqvist (1997), Zollner & Remler (1998), Lindkvist (2000), Demeyer et al. (2001). Values between brackets are extreme values, probably caused by contamination from waste material incineration.

Element	Wood fly ash	Peat fly ash	Coal fly ash
		%	
P	0.03 – 2.80	0.57 – 1.24	0 - 0.2
K	0.11 – 16.2	0.39 - 5	0.17 - 6.72
Ca	0.58 – 54.9	4.0 - 25	0.11 - 45
Mg	0 – 11.7	0.58 – 4.9	0 - 7.72
Na	0 – 13.4	0 – 1.48	0 -7.1
Al	0 – 12.2	2.9 – 11.2	0.1 - 21.7
Fe	0 – 12.6	1.5 – 14.7	1.0 - 27.6
Si	0 – 31	10 - 27	0 - 31.8
		$mg\ kg^{-1}$	
As	0 – 110	2 – 440	1 – 1 700
B	7.7 – 430 (800)	10 – 4 800	5 – 5 000
Cd	0 – 30 (140)	0 – 80	0 - 250
Cr	3.4 – 250 (1 040)	<5 – 500	1 – 7 400
Cu	1 – 600 (2 050)	5.7 – 650	0 – 3 000
Hg	0 – 1 (2.8)	0 – 5	0 - 80
Mn	0 – 23 000 (47 000)	700 – 15 000	25 – 4 400
Mo	<0.25 – 3 (123)	5 – 20	0.1 - 500
Ni	0 – 250 (360)	<5 – 700	1 – 4 300
Pb	1.2 – 500 (1 000)	<5 – 970	1 – 2 100
Se	0 – 100	3 – 5	0.2 - 130
V	3.4 – 120	<5 – 590	10 – 1 200
Zn	15 – 5 000 (10 000)	6 – 2 600	<8 – 13 000

Wood ash fertilization on peatlands

As wood ash contains relatively high concentrations of P and K, but also some important micronutrients, it was used as a fertilizer in peatland forestry experiments from a rather early stage. The first known wood ash fertilization trials on peatlands were established in the beginning of the 20th century on two drained peatlands, Södra Hällmyren and Norra Hällmyren, both located near Umeå in northern Sweden. In 1918, an area of 0.3 hectares on Södra Hällmyren received approximately 1 000 kg of loose wood ash, corresponding to a dose of 3 300 kg ha^{-1}. In 1926, approximately 2 000 kg of loose wood ash were spread on an area of 0.16 hectares on Norra Hällmyren. The amount spread on Norra Hällmyren corresponded to a dose of 12 500 kg ha^{-1}. Malmström (1935, 1943,

1952) investigated the vegetation, soil chemistry and the development of the tree stands on these two trials. He found a marked changed in ground vegetation and, especially on Norra Hällmyren, a vigorous growth of birch (*Betula pendula* Roth. and *B. pubescens* Erh.) on the ash fertilized plots. More than 20 years after the ash application on Norra Hällmyren, the pH and Ca content were still increased down to 20 cm depth. The concentrations of K and P were also raised in the upper 10 cm of the peat.

The results from Hällmyrarna inspired Malmström and other researchers to establish some small ash experiments on Swedish peatlands in the 1930s and 1940s (Malmström, 1952). However, in spite of the good experiences from Hällmyrarna, no large-scale application of wood ash was performed on peatlands in Sweden until 1984.

In Finland on the other hand, the results from Hällmyrarna and their own domestic research inspired, the Finnish Forest Research Institute among others, and during the period 1937-1959 about 30 ash experiments were established on drained peatlands. The introduction of commercial forest fertilizers decreased the interest in ash fertilization in the 1960s but as several of the Scots pine stands that were fertilized with wood ash in 1937-1959 were still growing vigorously in the 1970s, a new interest in wood ash fertilization on peatlands started in Finland at that time. About 170 ash experiments were established during the period 1977-1985 by the Finnish Forest Research Institute. Wood ash was mainly used in these experiments, but peat ash was also applied alone or together with wood ash (Silfverberg, 1996).

In Finland, some peat cutover peatlands were also fertilized with wood ash and afforested with Scots pine, downy or silver birch, grey alder and different Salix species (Kaunisto, 1987; Ferm and Hytönen, 1988; Kaunisto & Viinamäki, 1991; Hytönen, 1995a; Hytönen and Kaunisto, 1999). The application of wood ash usually has a substantial effect on the growth of these species.

Wood ash application on forest mineral soils

During the last 15 years several investigations have been performed in different forest ecosystems of Sweden, Finland, Germany, USA, Brazil, to study effect of wood ash application on the

- soil chemistry (Martikainen, 1984; Unger and Fernandez, 1990; Clarholm, 1994; Fritze et al., 1994; Bellote et al., 1995; Bramryd and Fransman, 1995; Kahl et al., 1996; Williams et al., 1996; Eriksson, H.M. 1998; Eriksson et al., 1998; Eriksson, J. 1998; Ring et al., 1999),
- soil biota (Martikainen, 1985; Bååth and Arnebrant, 1994; Fritze et al., 1994, 2000; Clarholm and Rosengren-Brinck, 1995; Clarholm, 1998; Lundkvist, 1998; Haimi et al., 2000; Mahmood et al., 2001),

- water chemistry (throughfall, soil water, groundwater and runoff) (Westling and Hultberg, 1990/91; Fransman and Nihlgård, 1995; Kahl et al., 1996; Williams et al., 1996; Büttner et al., 1998; Parkman and Munthe, 1998; Chirenje and Ma, 1999; Ring et al., 1999),
- ground vegetation (Gyllin and Kruuse, 1996; Kellner and Weibull, 1998; Jacobson and Gustafsson, 2001),
- plant and tree uptake (Unger and Fernandez, 1990; Clarholm and Rosengren-Brinck, 1995; Clarholm, 1998; Jönsson, 2000),
- germination and plant establishment (Thomas and Wein, 1990, 1994; Neéman et al., 1993; Karlsson, 1996),
- fine-root growth (Persson and Ahlström, 1994; Clemensson-Lindell and Persson, 1995) and
- tree productivity (McDonald et al., 1994; Bellote et al., 1995).

To summaries the results from all these studies very briefly, the environmental effects of wood ash application in moderate doses (1-3 tonnes ha^{-1}), are small compared to the corresponding effects following the harvest. Negative effects usually decrease with stabilisation treatments of the ash; loose ash > hardened and crushed ash > granulated ash.

Objectives

The main objective of this thesis was to evaluate how wood ash application affects elemental turnover on a cutover peatland and the uptake of elements in bilberry fruits on a mineral soil. Most of the work was conducted on a cutover peat area and the main questions in that study were:

1. Is there a vertical translocation of elements in the remaining peat and is this different for different elements?

2. How fast and in what amounts do the elements in ash leach to groundwater and stream water?

3. Is there a difference in nutrient plant uptake between different tree species and in what tree compartment do the elements accumulate?

4. Is there a difference in plant uptake of nutrients between lime-treated and wood ash-treated sites?

The main objective in Paper IV was to investigate how the application of different ash and lime products affects the uptake of nutrients and heavy metals in bilberry fruit. The main questions in this study were:

5. Has ash treatment (hardening, granulation) any effect on the short-term uptake of nutrients and heavy metals in bilberry fruit?
6. Is there a dose response for uptake of nutrients and heavy metals?

Study sites

The field work was conducted on two different sites in central Sweden (Fig. 1). Papers I, II and III are based on results from an abandoned peat harvested area on the Flakmossen mire, that was drained, fertilized with wood ash, raw phosphate, superphosphate, and rotovated. Paper IV is based on results from a field plot experiment on a mineral soil at Ärentuna, where different wood ash and lime products were applied in a 70-year-old mixed stand of Norway spruce and Scots pine. The site is described in Paper IV.

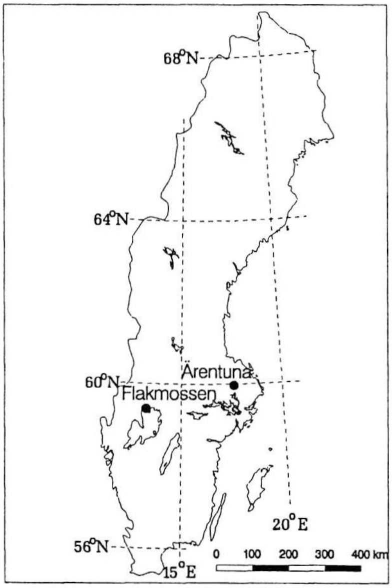

Fig. 1. Location of the study sites: Flakmossen in Papers I-III, Ärentuna in Paper IV.

The Flakmossen mire, being the main investigation site, is situated 10 km W of the city of Karlstad (59°23'N, 13°18'E, 65 m a.s.l.) in west-central Sweden (Fig. 1). The total area of Flakmossen mire is 160 ha and the surface slopes weakly towards south. As the area receives groundwater from an adjacent glaciofluvial deposit, the peatland can be characterised as a minerotrophic fen. Karlstad uses the glaciofluvial deposit as a water supply. In order to augment the natural replenishment of groundwater in this aquifer, surface water is pumped from Lake Vänern and infiltrated into the groundwater via special basins in the deposit. An unknown amount of the natural and artificial groundwater is transported to the peat area.

During the first half of the 20th century, peat harvesting was carried out on 34 ha of Flakmossen. The original peat layer on the peat harvesting area was 1-2.5 m thick and consisted mainly of sedge peat (Magnusson & Sandegren, 1933). At the end of the second world war, peat harvesting ceased and the main part of the cutover peat area was not used until the 1980s. In the beginning of the 1980s large areas were still bare peat surfaces and on the revegetated areas the field layer was dominated by a few species, *Phragmites communis*, *Rynchospora alba*, *Eriophorum angustifolium*, *Carex rostrata*, *Calluna vulgaris* and *Drosera* spp. (Fig. 2) (Eriksson, 1983). The thickness of the remaining peat layer on the abandoned peat harvesting area varied from 0.1 m up to nearly 2 m. A relatively undecomposed reed peat commonly constituted the main part of the remaining peat, while Sphagnum and woody peat often formed a minor part. Below the peat, a glaciofluvial medium sand was found. The soil type on the cutover peat area was classified as a Fibric Histosol (FAO, 1988).

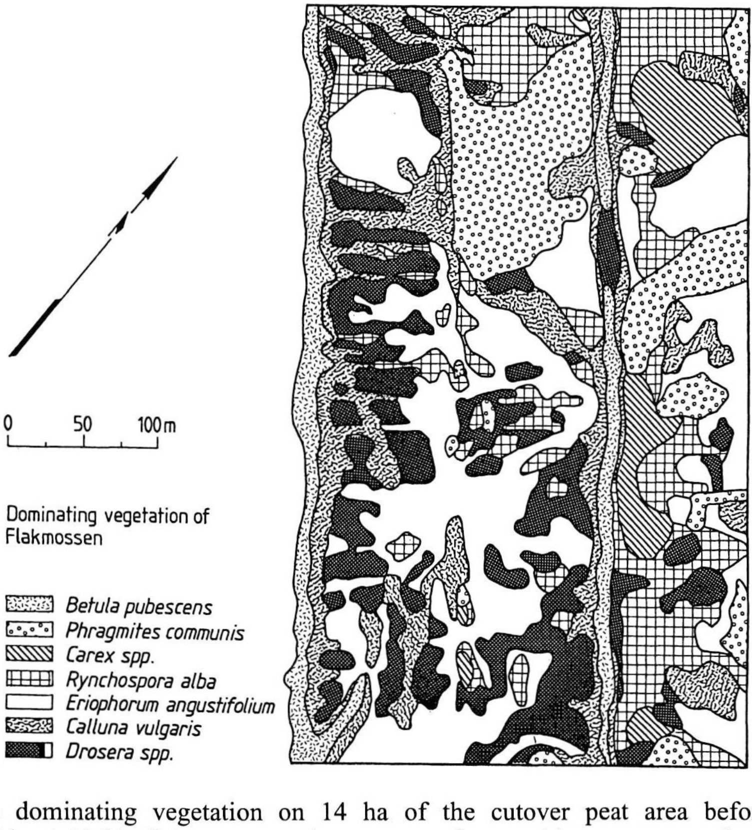

Fig. 2. The dominating vegetation on 14 ha of the cutover peat area before soil treatments. About 40 % of the area was bare peat surfaces, with some spots of vascular plants.

A small afforestation experiment (0.16 ha) was started in 1957 in the northern part of the cutover peat area (Fig. 3). Three plots (20x20 m) were fertilized with different doses of potassium sulphate and thomasphosphate. These plots, including a control plot, were broadcast sown with seeds from Norway spruce and Scots pine.

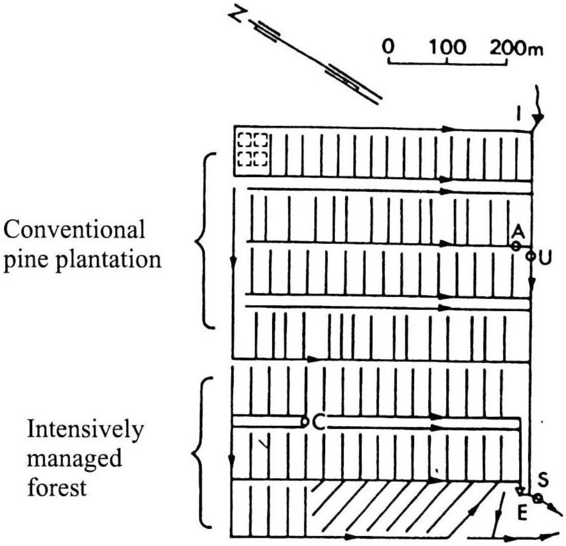

Fig. 3. Afforestation experiment areas, with ditch system, at the cutover peat area at Flakmossen mire. C = location of climate station, E and I = location of discharge gauging and water sampling stations. A, S and U = location of water sampling stations.

In 1982, 19 ha of the cutover peat area were drained and ploughed and a conventional pine plantation were established in 1983 by root-ball planting with Scots pine in the furrow slices (Fig. 3). The effects of different drain spacings (20 m, 30 m and 40 m) and PK doses (the pine seedlings were spot fertilized in 1984 with 0, 50, 100 or 200 g PK per seedling) were studied in that experiment.

The results in Papers I, II and III in this thesis are related to an intensively managed forest experiment that was established in 1983 on 14 ha of the cutover peat area (Fig. 3). The area was divided into 45 strips (90x30 m) by 0.7 m deep (on average) ditches. The soil spoil from the ditches was levelled out on the strips. As the thickness of the remaining peat layer varied between 0.1 to nearly 2 m, the bottom of the ditches extended into mineral soil (medium sand) in some areas. Consequently, some sand was excavated and spread on some of the strips. Fertilization with loose wood fly ash (23 000 kg ha^{-1}) and raw phosphate (400 kg ha^{-1}) on 42 strips was started in 1983 and ended in 1984. Two of the remaining strips received lime (7 500 kg ha^{-1}), potassium chloride (1 500 kg ha^{-1}) and raw phosphate (400 kg ha^{-1}), while the last remaining strip received only 800 kg raw phosphate per hectare. The wood ash was obtained from a pulp mill at Skoghall, 10 km SE of Flakmossen, and the chemical composition of the ash is described in

Papers I and III. The ash was applied with a tractor-drawn manure spreader. The amount of ash applied on the ash-treated strips was monitored by weighing the ash amount collected in vessels of a known area that were set out on the strips before fertilization. The amount of wood ash applied ranged from 16 000 kg dry weight to 33 000 kg dry weight per hectare. After fertilization the peat was rotovated to a depth of about 30 cm in 1 m wide strips with a tractor-drawn rotovator (Danfors et al., 1985) and superphosphate (250 kg ha^{-1}) was applied during the rotovation. The distance between the rotovated strips was 1.2 m. The 45 strips were divided into 97 plots (40 x 30 m). In late autumn 1983, 36 of these plots had been soil treated and were planted in spring 1984. The soil treatment on the remaining 61 plots was finished in summer 1984 and these were planted in spring 1985. Different tree species were planted on the plots: four-year-old *Picea abies* ((L.) Karst.), three-year-old *Pinus sylvestris* (L.), two-year-old *Betula pubescens* (Ehrh.), two-year-old *Alnus incana* ((L.) Moench), *Alnus glutinosa* ((L.) Gaertn.), 25-30 cm long cuttings of *Salix viminalis* (L.), and *Salix dasyclados* (Wimm.). The plants were placed in the rotovated strips.

Results and discussion

Effects of wood ash fertilization on cutover peatlands

Large doses of fertilizer are usually needed to establish a forest stand on a cutover peatland. Wood ash is a suitable fertilizer on such sites as it contains many nutrients and has an alkalising effect. However, applying large doses of wood ash on a cutover peatland will of course have some effects on the chemical composition of the soil, groundwater, stream water and eventually also on the vegetation and the fauna that may occur on such sites. On recently terminated peat harvest areas, the soil surface is mainly bare peat and the only vegetation found on such sites is usually growing in the ditches. Plant colonization of harvested peat surfaces is usually slow (Salonen, 1990) and this probably also results in a very low population of animals on these sites.

Effects on field layer vegetation

On the cutover peat area at Flakmossen, more than 35 years had passed after peat harvesting had terminated before a comprehensive soil treatment (drainage, fertilization with wood ash, raw phosphate and superphosphate, and rotovation) occurred. Consequently, some vegetation had succeeded in establishing on the cutover peat area before soil treatments were applied. However, about 40 % of the cutover peat area was still bare peat surface. Eriksson (1983) found 22 different vascular plants on this site before soil treatments and from that investigation the site could be characterized as a poor low sedge type (Hånell, 1984).

Drainage, supply of P with raw phosphate and superphosphate, and rotovation favour plant colonization of course, but the main reason for establishment of vegetation on the peat surface after the soil treatments was the large supply of wood ash (on average 23 000 kg ha^{-1}). Different weed species, especially *Epilobium angustifolium*, rapidly colonized the wood ash fertilized area. Similar effects have also been observed after silviculture measures with wood ash fertilization on drained peatlands (Malmström, 1935; Silfverberg, 1996).

An investigation on the vegetation cover performed in 1991, 7-8 years after the soil treatments, showed that the vegetation was dominated by pioneer and nitrophilic species (Eriksson, 1992). In total, 74 different vascular plant species were found and the most common and often dominating species were *Calamagrostis canescens, Tussilago farfara, Rubus idaea, Epilobium angustifolium, Circium arvense, Stellaria media* and *Urtica dioca*. The following nine species that occurred on the cutover peat area before the soil treatments were not found 7-8 years after the treatments; *Andromeda polifolia*, *Carex rostrata*, *Potentilla palustris*, *Scheucheria palustris*, *Empetrum nigrum*, *Rhynchospora fusca*, *Rhynchospora alba*, *Drosera anglica* and *Drosera intermedia*.

The changed vegetation cover after the soil treatments resulted in the site now being characterized as a low herb type according to the system by Hånell (1984). The observed changes in vegetation cover can probably mainly be ascribed to the wood ash fertilization.

Translocation within the peat and leaching of elements (Papers I and III)

The application of on average 23 000 kg wood ash, 400 kg raw phosphate and 250 kg superphosphate per hectare resulted in a large supply of different elements to the soil on the cutover peatland (Table 2 in Paper III). For all elements except P, the wood ash application was responsible for more than 90 % of the supply of different elements. Raw phosphate and superphosphate contributed about 34 % of the P supply. The fertilizer effect on the vertical distribution of elements in the peat was consequently mainly dependent on the wood ash supply. In Paper III, the concentrations and pools of N, P, K, Ca, Mg and Mn were investigated before soil treatments and one and three years after the treatment. Compaction of the peat, induced by the drainage, caused an increase in the pools for all elements down to 40 cm depth. This compaction-induced increase in the elemental pools down to 40 cm depth was estimated from the increase in the N pool to be about 50 %. After the soil treatments, the soil pools of the mineral elements studied (P, K, Ca, Mg and Mn) had increased by 63 – 1150 %, indicating that fertilization also increased these pools. However, three years after the fertilization, the main proportion of the elements supplied was still left in the upper 40 cm of the peat. After correction of the elemental pools for the peat compaction, there was even an increase in the P pool down to 40 cm depth of 160 kg ha^{-1}, which to some degree can be explained by spatial variation in the amounts of fertilizers applied and an uncertainty in P concentration of the whole amount of wood ash applied (300 tonnes). For the other mineral elements studied, losses were observed if the soil pools of these elements down to 40 cm depth were corrected for peat compaction. These losses amounted to between 27 % and 44 % of the fertilizer supply of these elements. The losses could not be explained by plant uptake (Paper II) or leaching to the stream water (Paper I). There are several explanations for the unaccounted losses. Some amounts are probably leached down to deeper soil layers and/or are dissolved in the large groundwater aquifer that is located in the mineral soil. There was also a large spatial variation in the amounts of wood ash applied. Furthermore, as there were only two chemical analyses of the wood ash material applied, a large uncertainty exists as regards the actual amount of elements supplied.

After the soil treatments, increased contents of K, Ca and Mn were found in both peat groundwater and stream water (Paper I). An increased content of Mg was also found in the stream water. However, the total leaching losses of these elements in stream water were at most only some percent of the losses found in the soil pool down to 80 cm.

The most obvious increase in groundwater and stream water concentrations of an element was found for K. Even 6-7 years after the fertilization a substantially higher K concentration was observed both in groundwater and stream water. The low degree of transport of P downwards in the peat and the low losses of P to stream water indicates an extensive adsorption of phosphate to iron compounds in the peat (Papers I and III). Other studies, especially on nutrient-poor bogs, have found substantial leaching of P after P fertilization (Karsisto and Ravela, 1971; Tamm et al., 1974; Harriman, 1978; Ahti, 1983, 1990, Malcolm and Cuttle, 1983; Kenttämies and Laine, 1984; Lundin and Bergquist, 1985; Nieminen and Ahti, 1993). The leaching of P from P-fertilized forests on peatlands may, according to these studies, vary between 0.1 – 2 kg ha^{-1} year^{-1}. Extremely high leaching losses of P (up to 30 kg ha^{-1} year^{-1}) have been reported from P fertilized peatlands used for agricultural crops (Duxbury and Peverly, 1978; Miller, 1979; Scheffer et al., 1981; Kuntze, 1984). The output of P from the intensively managed forest area on the cutover peatland at Flakmossen was only 0.02 kg P ha^{-1} year^{-1} which was even lower than the amount of 0.06 kg P ha^{-1} year^{-1}, that Sallantaus and Pätilä (1983) stated as normal P outputs from virgin peatlands in Finland.

Plant uptake and tree growth (Paper II)

The study on biomass production and nutrient uptake in the trees on the intensively managed forest area was performed on 3-7 year-old trees. The total biomass of these trees was consequently low and the proportions of foliage, bark and roots were high. The high proportion of foliage and bark in these trees resulted in a high uptake of nutrients per unit biomass (Table 5a,b in Paper II). There was a substantial difference in the above-ground biomass between the tree species (Table 3 in Paper II). The highest above-ground biomass was found for the stands of *Salix dasyclados* (9 300 kg DM ha^{-1}), while the lowest was found for stands of *Salix viminalis* (670 kg DM ha^{-1}). The difference can to a large degree be explained by the fact that the *Salix dasyclados* stands were planted in 1984 and the stands of the other tree species were planted in 1985. The growth of all tree species was much higher from for the plants planted in 1984 compared to those planted in 1985.

The *Alnus* sp. accumulated more N per unit biomass than the other tree species (Table 5a,b in Paper II), probably depending on the N-fixation capacity of *Alnus* sp. The uptake of P, K, Ca and Mg per unit biomass was also highest for the *Alnus* sp. The highest uptake of Zn were noted for the *Salix* clones. A high uptake of heavy metals in fast growing trees, like *Populus* species and *Salix* species, has been found in many studies (*e.g.* Landberg and Greger, 1996; Alriksson, 1998). Trees on plots, treated with lime (7 500 kg ha^{-1}) and KCl (1 500 kg ha^{-1}) instead of wood ash were also sampled and analyzed. A comparison between these two treatments showed that three years after the treatment the above-ground biomass of *B. pubescens* was significantly higher on the limed plots compared to wood ash treated plots. The conifers and the *Salix* clones were, on the other hand, somewhat larger on the wood ash treated plots. The content of P in the foliage was, on average, much higher for trees on the wood ash treated plots compared to the limed plots.

Potassium budget after wood ash fertilization on a cutover peatland

Potassium is a rather mobile nutrient and from many studies it is well known that large amount of applied K can easily and rather rapidly be leached from organic soils (*e.g.* Kenttämies and Laine, 1984; Lundin and Bergquist, 1985; Lumme, 1988; Brække, 1990). By making a budget study for K it is possible to forecast the depletion of the K pool in the soil and plan for prospective fertilizations, thereby maintaining a sustainable biomass production. As K is a nutrient with low abundance in peatlands, and especially in cutover peatlands, it is often a major limiting growth factor on these sites. Case budget studies of K on such sites are therefore particularly interesting.

By using the information from Papers I, II and III and adding information about K deposition, it is possible to make a simple budget for K for the wood ash fertilized part of the cutover peat area on Flakmossen. The structure of this simple K budget can be described as transfers of K to or from a pool of K in the soil. I have only used the soil K pool in the upper 80 cm of the soil, as the soil was only sampled down to this depth. This is of course a restriction, as the total soil depth probably exceeded 3 m over the whole area. However, we expected that most of the mineralisation and root uptake occurred in the upper 80 cm of the peat since deeper soil layers were saturated with water during the whole or significant parts of the year.

Transfers of K

Potassium was added to the soil K pool by wet and dry deposition, and on this site also by wood ash fertilization, and transferred from the soil by leaching. In this part of Sweden the mean concentration of K in the precipitation was about 2 μekv l^{-1} during the period 1983-1987 (Granat, 1989). During this period the mean annual precipitation amount at Karlstad was 730 mm. This means that the mean annual wet deposition of K on this site was about 0.57 kg ha^{-1}. The total wet deposition of K during the first 3-year period after soil treatments was consequently 1.7 kg ha^{-1}. As all the trees on the site except the willows were quite small during this period, the dry deposition over the whole site was probably rather low (<50 % of wet deposition). Consequently, the total atmospheric deposition (wet + dry) on the wood ash fertilized area was probably less than 3 kg ha^{-1} for the first 3-year period after soil treatments.

On the wood ash fertilized area, the wood ash was the only fertilizer that contained substantial amounts of K. The mean concentration of K in the ash was 2.9 % of dry weight. With an average dose of 23 000 kg dry wood ash per hectare, the total K amount supplied was about 670 kg ha^{-1}.

The loss of K from the upper 80 cm of the soil pool through leaching can be calculated by comparing the output of K in stream water from the wood ash fertilized area before and after fertilization. Runoff from the intensively managed area was measured continuously with a discharge weir and water samples were taken in that weir once a month. Before soil treatments, the K concentration in the stream water averaged 1.07 mg l^{-1}. In the first 3-year period after the soil treatments, the mean K concentration in stream water increased to 1.99 mg l^{-1}. In the stream water from a control area, the mean K concentration decreased somewhat during this period, which indicates that the increase in K concentration in stream water from the wood ash fertilized area was mainly caused by the fertilization. As other studies have observed increased leaching of K after drainage of unfertilized peatlands (Kenttämies and Laine, 1984; Ahtiainen, 1988; Lundin, 1988, 1992; Lundin and Bergquist, 1990), a proportion of the increased K concentration found in our study (Paper I) may have been caused by the drainage. However, the increases in K in stream water in our study coincided more closely with the fertilization events than with the drainage treatment. The mean annual runoff during the first 3-year period after the soil treatments was 260 mm $year^{-1}$. The mean annual excess leaching of K from the wood ash fertilized area during this 3-year period was consequently about 2.4 kg ha^{-1} $year^{-1}$ or 7.2 kg ha^{-1} for the whole 3-year period. Several other peatland studies have also found increased K concentrations in stream water after application of fertilizers containing K (Burke, 1975; Harriman, 1978; Ahti, 1983; Malcolm and Cuttle, 1983; Lundin and Bergquist, 1985; Lumme, 1988; Brække, 1990; Piirainen and Finér, 2000).

From the tables of concentrations in different tree compartments (Tables 4a-b in Paper II), the proportion of different compartments to the total biomass (from Table 3 in Paper II) and values of measured or calculated stem dry weight of the different tree species on the plots within the wood ash fertilized area, a rough figure could be estimated for the net biomass uptake of K. Three years after soil treatments, the age of the planted trees was only 3-7 years and the total biomass of the trees was therefore low and consequently also the total uptake (Paper II) and the net biomass uptake of K. The accumulated net biomass uptake of K within the wood ash fertilized area (13 ha) was estimated to be on average about 20 kg ha^{-1}.

There were no measurements performed on the biomass or nutrient content of the field layer vegetation. A rough estimation is that the uptake of K was in the same order as for the trees, but as most of this K in the field layer vegetation was probably returned to the soil in late autumn, no value for K uptake by the field layer vegetation was used.

Soil K pool

Before soil treatments, the pool of K down to 80 cm depth was only 130 kg ha^{-1} (Table 3 in Paper III). The drainage caused a compaction, especially of the superficial peat layers, resulting in the fact that the peat sampling down to 80 cm depth after drainage encompassed a larger soil mass than before drainage. This also led to the fact that the nutrient pools of a depth-specified peat layer within the compacted zone increased after drainage. The compaction-induced increase in the K-pool down to 80 cm depth was calculated to be about 35 kg ha^{-1}.

Three years after the soil treatment, the total K pool down to 80 cm depth was 580 kg ha^{-1}. Correcting this value for the increase caused by the compaction gives a value of 545 kg ha^{-1}. The increase in the soil K pool of 415 (=545-130) kg ha^{-1} is mainly a result of the wood ash fertilization. As 670 kg K per hectare was applied, the loss of K from this soil pool during the 3-year period was about 255 kg K ha^{-1} or 38 % of the applied amount.

Input/output budget

For a system in balance the input fluxes should equal the output fluxes. However, in field experiments it is hard to exactly define all the fluxes and with increasing spatial scale the uncertainty usually also increases. The input/output budget for K at the wood ash fertilized area was as follows:

$$F + D - U - L - \Delta S = 0$$

where F denotes K applied through fertilization, D deposition, U net biomass uptake, L leaching and ΔS the change in the soil pool down to 80 cm depth. Inserting the values from the wood ash fertilized area for the first 3-year period after soil treatments gives as follows:

$$670 + 3 - 20 - 7 - 415 = 231$$

This means that in this system, a loss of 231 kg K ha^{-1} cannot be accounted for. However, a groundwater leakage out from the system can be one probable explanation.

Uptake of elements in bilberry fruit (Paper IV)

As wood ash also contains small amounts of heavy metals, fears have been raised that wood ash application on forest soils might increase the uptake of heavy metals in edible berries and mushrooms gathered and consumed by humans. In Paper IV, we investigated the concentrations of nutrients and heavy metals in bilberry fruit that was sampled two and thirteen months after application of the following eight wood ash and lime products: loose ash; well-hardened ash granules; fly ash that had been hardened, crushed and sieved; two different particle size fractions of the hardened and crushed ash mixed with lime; two different particle size fractions of a hardened bottom ash; and lime. The normal dose were 4 000 kg ha^{-1}, but the loose ash and the hardened fly ash were also applied in doses of 2 000 kg ha^{-1} and 8 000 kg ha^{-1}.

Two months after treatments, bilberries from treated plots tended to have higher contents of K, Mg, Ca and Cu, and lower contents of Cd, Pb and Zn compared to bilberries from control plots. Thirteen months after treatments, the bilberries from almost all treatments tended to have higher contents of Cd, Cu, Pb and Zn than berries from control plots (Table 3, 4 and 6 in Paper IV). However, all these possible treatment effects were only tendencies and no significant treatment effect could be found. Consequently, this study showed that the short-term effects of wood ash application on the concentrations of nutrients and heavy metals in bilberry fruit is negligible. Possible long-term effects remain to be tested.

Conclusions

At afforestation on cutover peatlands wood ash fertilization is a suitable soil improvement measure, because wood ash contains large quantities of nutrients, especially P and K, that are growth-limiting factors in such areas. Furthermore, as wood ash is an alkalising agent it raises the soil pH, which is often low in peatlands. However, as large doses of wood ash are often needed, negative effects may occur. The negative effects on cutover peatland sites are mainly effects on the water quality in downstream watercourses. A large proportion of the K in wood ash is in the form of soluble salts, so large quantities of K can be leached from the ash. Potassium is a mobile element in organic soils and substantial amounts of K may therefore be exported to the water courses. However, within reasonable bounds, increased concentrations of K in the watercourses do not cause any harmful effects on the ecosystem. On the other hand, the continuous transport of K from the soil pool may in the long-term cause a negative effect on tree growth. The wood ash product used on cutover peatlands sites should therefore be in such a form that the K release from the ash is relatively low.

The uptake of different ash elements in trees planted on the wood ash treated area of the cutover peatland seemed to be specific for different species. A high uptake of Zn, and probably also other heavy metals, was observed for the two *Salix* clones. The conifers, on the other hand, had a low uptake of Zn and Mg, but a high accumulation of Mn in the biomass. The largest uptake per unit biomass of N, P, K Ca and Mg was observed for the alder species. If this condition persists in the long-term, alder may not be a suitable tree species on this kind of site.

Wood ash application on a mineral soil may cause more problems than the corresponding measure on cutover peatlands as the populations of different plant and animal species are usually higher on the mineral soil site. From the work presented here, it can be concluded that in the short-term there are no significant negative effects on the uptake of nutrients and heavy metals in fruit of bilberries growing on sites treated with loose ash, hardened and crushed ash, or granulated ash products in different doses. However, longer term studies are needed to confirm this finding and to monitor the composition of other edible forest flora and fauna, such as fungi and game animals.

References

Ahti, E. 1983. Fertilizer-induced leaching of phosphorus and potassium from peatlands drained for forestry. *Communicationes Instituti Forestalis Fenniae 111*, 1-20.

Ahti, E. 1990. Fertilizer-induced leaching of elements from oligotrophic peat. *In: Hånell, B. (Ed.). Proceedings Biomass production and element fluxes in forested peatland ecosystems. Umeå, Sweden, September 3-7, 1990*, 139-156.

Ahtiainen, M., 1988. Effects of clear-cutting and forest drainage on water quality in the Nurmes-study. *Symposium on the hydrology of wetlands in temperate and cold regions. Joensuu, Finland, 6-8 June 1988. Vol. I*, 206-219.

Alriksson, A. 1998. Afforestation of Farmland – Soil changes and the uptake of heavy metals and nutrients by trees. Doctoral thesis. *Acta Universitatis Agriculturae Sueciae, Silvestria 57.*

Anon. 2000a. Energy in Sweden 2000. Swedish National Energy Administration. 1-44.

Anon. 2000b. Peat 1999. Resources, use, environmental impact. Statistiska centralbyrån, *Statistiska meddelanden, Serie Mi 25.* 1-44. (In Swedish, with English summary).

Anon. 2001a. Rekommendationer vid uttag av skogsbränsle och kompensationsgödsling. *Swedish National Board of Forestry, Jönköping, Sweden, Meddelande nr 2/2001*, 19 pp. (In Swedish).

Anon. 2001b. Torvåret 2000. Statistik över Sveriges torvproduktion 2000. Sammanställd av Svenska Torvproducentföreningen. 2001. 1-12. (In Swedish).

Bååth, E. and Arnebrant, K. 1994. Growth rate and response of bacterial communities to pH in limed and ash treated forest soils. *Soil Biology & Biochemistry 26*, 995-1001.

Bellote, A.F.J., Ferreira, C.A., Silva, H.D. and Andrade, G.C. 1995. Effects of the application of ash and pulp residues on the soil and on the growth of Eucalyptus grandis. (In Spanish, with English summary). *Bosque 16*, 95-100.

Bramryd, T. & Fransman, B. 1995. Silvicultural use of wood ashes - effects on the nutrient and heavy metal balance in a pine (*Pinus sylvestris* L.) forest soil. *Water, Air and Soil Pollution 85*, 1039-1044.

Brække, F.H. 1979. Boron deficiency in forest plantations on peatland in Norway. *Reports of the Norwegian Forest Research Institute 35*, 213-236.

Brække, F.H. 1990. Drainage and fertilization of low-shrub pine bogs - a summary of changes in bulk density and mineral-element stores. *In: Hånell, B. (Ed.). Proceedings-Biomass production and element fluxes in forested peatland ecosystems. Umeå, Sweden, September 3-7, 1990*, pp: 57-63.

Burke, W. 1975. Fertiliser and other chemical losses in drainage water from blanket bog. *Irish Journal of Agricultural Resarch 14*, 163-178.

Büttner, G., Gering, C., Nell, U., Rumpf, S. & Wilpert, K. 1998. Einsatz von Holzasche in Wäldern. *Forst und Holz 53*, 72-76.

Campbell, A.G. 1990. Recycling and disposing of wood ash. *Tappi Journal 73(9)*, 141-146.

Campbell, A.G., Zhang, X. & Tripepi, R.R. 1995. Composting and evaluating a kraft pulp and paper sludge for use as a soil amendment. *Compost Science & Utilization 3*, 84-95.

Campbell, A.G., Folk, R.L. & Tripepi, R.R. 1997. Wood ash as an amendment in municipal sludge and yard waste composting processes. *Compost Science & Utilization 5*, 62-73.

Carpenter, A., & Beecher, N. 1997. Wood ash finds niche in biosolids composting. *BioCycle 38*, 37-39.

Chirenje, T. and Ma, L.Q. 1999. Effects of acidification on metal mobility in a papermill-ash amended soil. Journal of Environmental Quality 28, 760-766.

Clapham, W.M. & Zibilske, L.M. 1992. Wood ash as a liming amendment. *Communications in Soil Science and Plant Analysis 23*, 1209-1227.

Clarholm, M. 1994. Granulated wood ash and a 'N-free' fertilizer to a forest soil - effects on P availability. *Forest Ecology and Management 66*, 127-136.

Clarholm, M. 1998. Wood ash to counteract potential phosphorus and potassium limitations in a Norway spruce forest subjected to air pollution. *Scandinavian Journal of Forest Research, Supplement No. 2*, 67-75.

Clarholm, M. & Rosengren-Brinck, U. 1995. Phosphorus and nitrogen fertilization of a Norway spruce forest - effects on needle concentration and acid phosphatase activity in the humus layer. *Plant and Soil 175*, 239-249.

Clemensson-Lindell, A. and Persson, H. 1995. Fine-root vitality in a Norway spruce stand subjected to various nutrient supply. *Plant and Soil 168-169*, 167-172.

Danfors, B., Stambeck, A. and Åsberg, G. 1985. Spridning och djupmyllning av kalk vid anläggning av energiskog. *Jordbrukstekniska institutet, Uppsala. JTI-rapport 65*, 38 p. (In Swedish).

Demeyer, A., Voundi Nkana, J.C. and Verloo, M.G. 2001. Characteristics of wood ash and influence on soil properties and nutrient uptake: an overview. *Bioresource Technology 77*, 287-295.

Dooley, M., Dickinson, C.H. 1971. The ecology of fungi in peat. *Irish Journal of Agricultural Research 10*, 195-206.

Duxbury, J.M. and Peverly, J.H. 1978. Nitrogen and phosphorus losses from organic soils. *Journal of Environmental Quality 7*, 566-570.

Eary, L.E., Rai, D., Mattigod, S.V. and Ainsworth, C.C. 1990. Geochemical factors controlling the mobilization of inorganic constituents from fossil fuel combustion residues: II. Review of the minor elements. *Journal of Environmental Quality 19*, 202-214.

Eggelsmann, R. 1988. Rewetting for protection and renaturation/regeneration of peatland after or without peat winning. *Proceedings of the 8th International Peat Congress*, Leningrad, 1988. Volume 3, 251-260.

Egnell, G., Nohrstedt, H.-Ö., Weslien, J., Westling, O. and Örlander, G. 1998. Miljökonsekvensbeskrivning (MKB) av skogsbränsleuttag, asktillförsel och övrig näringskompensation. *Skogsstyrelsen Rapport 1/1998*, 170 p. (In Swedish).

Erich, M.S. 1991. Agronomic effectiveness of wood ash as a source of phosphorus and potassium. *Journal of Environmental Quality 20*, 576-581.

Eriksson, F. 1983. Vegetationskartering av Flakmossen i augusti 1983. *Manuscript, Department of Limnology, University of Uppsala*, 6 p. (In Swedish).

Eriksson, H.M. 1998. Short-term effects of granulated wood ash on forest soil chemistry in SW and NE Sweden. *Scandinavian Journal of Forest Research, Supplement No. 2*, 43-55.

Eriksson, H.M., Nilsson, T. & Nordin, A. 1998. Early effects of lime and hardened and non-hardened ashes on pH and electrical conductivity of the forest floor, and relations to some ash and lime qualities. *Scandinavian Journal of Forest Research, Supplement No. 2*, 56-66.

Eriksson, J. 1992. Characterization of wood ash with respect to contents and solubility of plant nutrients and heavy metals. *Vattenfall Research Bioenergy, Vällingby, Sweden. FUD-Rapport U(B) 1992/48*, 1-38. (In Swedish, with English summary).

Eriksson, J. 1998. Dissolution of hardened wood ashes in forest soils: Studies in a column experiment. *Scandinavian Journal of Forest Research, Supplement No. 2*, 23-32.

Etiegni, L., Campbell, A.G. & Mahler, R.L. 1991. Evaluation of wood ash disposal on agricultural land. I. Potential as a soil additive and liming agent. *Communications in Soil Science and Plant Analysis 22*, 243-256.

FAO. 1988. Soil map of the world. Revised legend. *World Soil Resources Report 60, FAO, Rome*, 117 p.

Ferda, J. 1975. Forestry reclamation of extracted peat deposits. Research institute for land reclamation and improvement, Praha. *Scientific monographs 6/1975*, 193 p.

Ferda, J., 1986. Reclamation and utilization of extracted peat deposits for forest planting. In: *Socio-eco-nomic impacts of the utilization of peatlands in industry and forestry.* Proc. of the IPS Sympo-sium, Oulu, Finland, June 9-13, 1986, 227-239.

Ferm, A. and Hytönen, J. 1988. Effect of soil amelioration and fertilization on the growth of birch and willow on cut-over peat. *Proceedings 8th International Peat Congress, Leningrad 1988. Vol. 3*, 268-279.

Ferm, A., Hokkanen, T., Moilanen, M. & Issakainen, J. 1992. Effects of wood bark ash on the growth and nutrition of a Scots pine afforestation in central Finland. *Plant and Soil 147*, 305-316.

Fransman, B. & Nihlgård, B. 1995. Water chemistry in forested catchments after topsoil treatment with liming agents in south Sweden. *Water, Air and Soil Pollution 85*, 895-900.

Fredriksson, D. 1996. Peat resources in Sweden. In: Lappalainen, E. (Ed.), *Global peat resources.* International Peat Society, Finland, pp: 137-144.

Fritze, H., Smolander, A., Levula, T., Kitunen, V. & Mälkönen, E. 1994. Wood-ash fertilization and fire treatments in a Scots pine forest stand: Effects on the organic layer, microbial biomass, and microbial activity. *Biology and Fertility of Soils 17*, 57-63.

Fritze, H., Perkiömäki, J., Saarela, U., Katainen, R., Tikka, P., Yrjälä, K., Karp, M., Haimi, J. and Romantschuk, M. 2000. Effect of Cd-containing wood ash on the microflora of coniferous forest humus. *FEMS Microbiology Ecology 32*, 43-51.

Gradeckas, A., Kubertaviciene, L and Gradeckas, A. 1998. Utilization of wastewater sludge as a fertilizer in short rotation forests on cut away peatlands. *Baltic Forestry 4*, 7-12.

Granat, L. 1989. Luft- och nederbördskemiska stationsnätet inom PMK. Rapport från verksamheten 1988. *Statens naturvårdsverk, Rapport 3649*, 64 p. (In Swedish).

Greger, M., Hamza, K. and Perttu, K. 1995. Recirculation of waste products from forest industry – a prestudy. *Swedish Waste Research Council, AFR-Report 68*, 28 p.

Gyllin, M. & Kruuse, A. 1996. Effekter på floran efter tillförsel av ved- och blandaska. NUTEK R 1996:36, 1-23. (In Swedish, with English summary).

Hackett, G.A.R., Easton, C.A. & Duff, S.J.B. 1999. Composting of pulp and paper mill fly ash with wastewater treatment sludge. *Bioresource Technology 70*, 217-224.

Haimi, J., Fritze, H. & Moilanen, P. 2000. Responses of soil decomposer animals to wood-ash fertilisation and burning in a coniferous forest stand. *Forest Ecology and Management 129*, 53-61.

Hånell, B. 1984. Post-drainage site index of peatlands in Sweden. Swedish University of Agricultural Sciences, Department of Forest Soils, *Reports in Forest Ecology and Forest Soils, Report 50*, 128 p. (In Swedish, with English summary).

Hånell, B. 1989. Peatlands in Sweden: a description of forest conditions on shallow and deep peatlands and their national and local distribution. Swedish University of Agricultural Sciences, Department of Forest Soils, *Reports in Forest Ecology and Forest Soils, Report 60*, 88 p. (In Swedish, with English summary).

Harriman, R. 1978. Nutrient leaching from fertilized forest watersheds in Scotland. *Journal of Applied Ecology 15*, 933-942.

Havelka, F. 1988. Fertilizing and utilization of exploited peat beds in Czechoslovakia. *Proceedings of the 8th International Peat Congress*, Leningrad 1988. Volume 3, 280-287.

Holmen, H. 1969. Afforestation of peatlands. Kungl. *Skogs- och Lantbruksakademiens Tidskrift 108*, 216-235. (In Swedish, with English summary).

Huang, H., Campbell, A.G., Folk, R. & Mahler, R.L. 1992. Wood ash as a soil additive and liming agent for wheat: field studies. *Communications in Soil Science and Plant Analysis 23*, 25-33.

Hytönen, J. 1995a. Effect of fertilizer treatment on the biomass production and nutrient uptake of short-rotation willow on cut-away peatlands. *Silva Fennica 29*, 21-40.

Hytönen, J. 1995b. Biomass production with willows on cut-over peatland areas. In: *Peat Industry and Environment*, Pärnu, Estonia, 12-15 September, 1995, 93-95.

Hytönen, J. and Kaunisto, S. 1999. Effect of fertilization on the biomass production of coppiced mixed birch and willow stands on a cut-away peatland. *Biomass and Bioenergy 17*, 455-469.

Jacobson, S. and Gustafsson, L. 2001. Effects on ground vegetation of the application of wood ash to a Swedish Scots pine stand. *Basic and Applied Ecology 2*, 233-241.

Jacobson, S., Kukkola, M., Mälkönen, E. and Tveite, B. 2000. Impact of whole-tree harvesting and compensatory fertilization on growth of coniferous thinning stands. *Forest Ecology and Mangement 129*, 41-51.

Jönsson, A.M. 2000. Mineral nutrients of beech (Fagus sylvatica) bark in relation to frost sensitivity and soil treatments in southern Sweden. *Annals of Forest Science 57*, 1-8.

Joosten, H. 1997. European mires: a preliminary status report. *International Mire Conservation Group Members Newsletter 3*, 10-13.

Kahl, J.S., Fernandez, I.J., Rustad, L.E. & Peckenham, J. 1996. Threshold application rates of wood ash to an acidic forest soil. *Journal of Environmental Quality 25*, 220-227.

Karlsson, A. 1996. Initial seedling emergence of hairy birch and silver birch on abandoned fields following different site preparation regimes. *New Forests 11*, 93-123.

Karsisto, K. and Ravela, H. 1971. Washing away of phosphorus and potassium from areas drained for forestry and topdressed at different times of the year. *Acta Agralica Fennica 123*, 54-69.

Kaunisto, S. 1987. Effect of fertilization and soil preparation on the development of Scots pine and silver birch plantations on peat cutover areas. *Folia Forestalia 681*, 1-23. (In Finnish, with English summary).

Kaunisto, S. and Päivänen, J. 1985. Forest regeneration and afforestation on drained peatlands. A literature review. *Folia Forestalia 625*, 1-75. (In Finnish, with English summary).

Kaunisto, S. and Viinamäki, T. 1991. Effect of fertilization and alder (*Alnus incana*) mixture on the development of young Scots pine (*Pinus sylvestris*) trees and the peat properties in a peat cutover area at Aitoneva, southern Finland. Suo 42, 1-12. (In Finnish, with English summary).

Kaunisto, S. & Aro, L. 1996. Forestry use of cut-away peatlands. In: Vasander, H. (Ed.), *Peatlands in Finland.* Finnish Peatland Society, Helsinki, Finland, 130-134.

Kellner, O. & Weibull, O. 1998. Effects of wood ash on bryophytes and lichens in a Swedish pine forest. *Scandinavian Journal of Forest Research, Supplement No. 2*, 76-85.

Kenttämies, K. and Laine, J. 1984. The effects on water quality of forest drainage and phosphate fertilization in a peatland area in central Finland. *Proceedings of the 7th International Peat Congress, Dublin. 18-23 June 1984. Vol. III*, 342-354.

Kofman, P.D. 1987. Wood-ashes from chip fuelled heating plants: Chemical composition, possibilities of application. *The Danish Institute of Forest Technology, Frederiksberg, Denmark. SI 3-1987*, 20 p. (In Danish, with English summary).

Kolari, K.K. (Ed.). 1983. Growth disturbances of forest trees. *Communicationes Instituti Forestalis Fenniae 116*, 1-208.

Krasilnikova, L.Y., Kuznetsova, L.M., Lashnev, V.I. & Smelovski, V.E. 1986. Trends of cutover peatland utilization. In: *Socio-economic Impacts of the Utilization of Peatlands in Industry and Forestry.* Proceedings of the IPS Symposium, Oulu, Finland, June 9-13, 1986, 247-249.

Krejsl, J.A., & Scanlon, T.M. 1996. Evaluation of beneficial use of wood-fired boiler ash on oat and bean growth. *Journal of Environmental Quality 25*, 950-954.

Kreshtapova, V.N., Krupnovand, R.A. & Uspenskaya, O.N. 2000. Quality of peat soils of cutover peatlands in Russia: methods for determination and assessment criteria. *Proceedings of the 11th International Peat Congress*, Quebec City, Canada, August 6-12, 2000, Volume II, 1065.

Kukkonen, S., Uosukainen, M. & Vestberg, M. 1999. Cultivation of strawberry on mined peat bogs. In: Halko, L. & Myllys, M. (Eds.): *Chemical, Physical and Biological Processes in Peat Soils.* Abstracts from an international peat symposium, Jokioinen, Finland, 23-27 August, 1999, 99.

Kuntze, H. 1984. The risks of water pollution by agricultural utilization of peatlands and practical defenses. *Proceedings of the 7th International Peat Congress, Dublin, 18-23 June 1984, Vol. I*, 246-267.

Landberg, T. and Greger, M. 1996. Differences in uptake and tolerance to heavy metals in *Salix* from unpolluted and polluted areas. *Applied Geochemistry 11*, 175-180.

Lappalainen, E. 1996. *Global peat resources*. International Peat Society. 359 p.

Larsson, L.-E. 1982. Torvtillgångar i Sverige. Nämnden för energiproduktionsforskning, *NE 1982:11*. 67 p + app. (In Swedish, with English summary).

Lauhanen, R., Moilanen, M., Silfverberg, K., Takamaa, H. & Issakainen, J. 1997. The profitability of wood ash-fertilizing on drained peatland Scots pine stands. *Suo 48*, 71-82.

Lerner, B.R., Utzinger, J.D. 1986. Wood ash as soil liming material. *HortScience* 21, 76-78.

Lindkvist, L. 2000. Aska från biobränsle – produktions- och kvalitetsaspekter beträffande näringskompensation och vitalisering av skogsmark. *Skogsstyrelsen Rapport 2000:5*, 31 p. (In Swedish).

Logsdon, G. 1989. Odor control with bioash, *BioCycle 30*, 30-31.

Lumme, I. 1988. Early effects of peat ash on growth and mineral nutrition of the silver birch (*Betula pendula*) on a mined peatland. *Silva Fennica 22*, 99-112.

Lundin, L., 1988. Impacts of drainage for forestry on runoff and water chemistry. *Symposium on the Hydrology of Wetlands in Temperate and Cold Regions. Joensuu, Finland, 6-8 June 1988. Vol. I*, 197-205.

Lundin, L. 1992. Hydrology and hydrochemistry at subbasins of a large sedge fen watershed and effects of drainage and peat-winning. *Proceedings of the 9th International Peat Congress, Uppsala, Sweden. 22-26 June 1992. Vol. 1*, 143-157.

Lundin, L. and Bergquist, B. 1985. Peatland fertilization. Short-term chemical effects on runoff water. *Studia Forestalia Suecica 171*, 18 pp.

Lundin, L. and Bergquist, B. 1990. Effects on water chemistry after drainage of a bog for forestry. *Hydrobiologia 196*, 167-181.

Lundkvist, H. 1998. Wood ash effects on enchytraeid and earthworm abundance and enchytraied cadmium content. *Scandinavian Journal of Forest Research, Supplement No. 2*, 86-95.

Magnusson, N.H. and Sandegren, R. 1933. Beskrivning till kartbladet Karlstad. *Sveriges geologiska undersökning, Serie Aa nr 174*, 118 p. (In Swedish).

Mahmood, S., Finlay, R.D., Erland, S., Wallander, H. 2001. Solubilisation and colonisation of wood ash by ectomycorrhizal fungi isolated from a wood ash fertilised spruce forest. *FEMS Microbiology Ecology 35*, 151-161.

Malcolm, D.C. and Cuttle, S.P. 1983. The application of fertilizers to drained peat. 1. Nutrient losses in drainage. *Forestry 56*, 155-174.

Malmström, C. 1935. Om näringsförhållandenas betydelse för torvmarkers skogsproduktiva förmåga. *Meddelande från Statens Skogsförsöksanstalt 28*, 571-650. (In Swedish, with German summary).

Malmström, C. 1943. Skogliga gödslingsförsök på dikade svaga torvmarker. *Norrlands Skogsvårdsförbunds Tidskrift 4*, 273-292. (In Swedish).

Malmström, C. 1952. Svenska gödslingsförsök för belysande av de näringsekologiska villkoren för skogsväxt på torvmark. *Communicationes Instituti Forestalis Fenniae 40(17)*, 1-27.

Malterer, T.J. & Johnson, K.W. 1998. Perspectives on peatland restoration and reclamation in the United States. In: Malterer, T., Johnson, K. and Stewart, J. (Eds.), *Peatland Restoration & Reclamation – Techniques and Regulatory Considerations.* Proceedings of the International Peat Symposium, Duluth, Minnesota, 14-18 July, 1998, pp: 9-12.

Martikainen, P.J. 1984. Nitrification in two coniferous forest soils after different fertilization treatments. *Soil Biology & Biochemistry 16*, 577-582.

Martikainen, P.J. 1985. Numbers of autotrophic nitrifiers and nitrification in fertilized forest soil. *Soil Biology & Biochemistry 17*, 245-248.

Mattigod, S.V., Rai, D., Eary, L.E. and Ainsworth, C.C. 1990. Geochemical factors controlling the mobilization of inorganic constituents from fossil fuel combustion residues: I. Review of the major elements. *Journal of Environmental Quality 19*, 188-201.

McDonald, M.A., Hawkins, B.J., Prescott, C.E. and Kimmins, J.P. 1994. Growth and foliar nutrition of western red cedar fertilized with sewage sludge, pulp sludge, fish silage, and wood ash on northern Vancouver Island. *Canadian Journal of Forest Research 24*, 297-301.

Meyers, N.L. and Kopecky, M.J. 1998. Industrial wood ash as a soil amendment for crop production. *Tappi Journal 81(4)*, 123-130.

Miller, M.H. 1979. Contribution of nitrogen and phosphorus to subsurface drainage water from intensively cropped mineral and organic soils in Ontario. *Journal of Environmental Quality 8*, 42-48.

Misra, M.K., Ragland, K.W. and Baker, A.J. 1993. Wood ash composition as a function of furnace temperature. *Biomass and Bioenergy 4*, 103-116.

Mitchell, C.C. and Black, E.D. 1997. Land application of boiler wood ash in the southeastern United States. *American Chemical Society, Symposium Series 668*, 204-225.

Muse, J.K. and Mitchell, C.C. 1995. Paper mill boiler ash and lime by-products as soil liming materials. *Agronomy Journal 87*, 432-438.

Naylor, L.M. and Schmidt, E.J. 1986. Agricultural use of wood ash as a fertilizer and liming material. *Tappi Journal 69(10)*, 114-119.

Naylor, L.M. and Schmidt, E. 1989. Paper mill wood ash as a fertilizer and liming material: field trials. *Tappi Journal 72(6)*, 199-206.

Neéman, G., Meir, I. and Neéman, R. 1993. The effect of ash on the germination and early growth of shoots and roots of Pinus, Cistus and annuals. *Seed Science & Technology 21*, 339-349.

Nick, K.-J. 1984. Measures and chances of success for the regeneration of bogs after the complete industrial cutting of peat. *Proceedings of the 7th International Peat Congress*, Dublin, June 18-23, 1984, Volume 1, 331-338.

Nieminen, M. and Ahti, E. 1993. Leaching of nutrients from an ombrotrophic peatland area after fertilizer application on snow. *Folia Forestalia 814*, 1-22. (In Finnish, with English summary).

Nilsson, J. and Timm, B. 1983. Miljöeffekter av ved- och torvförbränning. *Statens naturvårdsverk PM 1708*, 232 p. (In Swedish, with English abstract).

Nilsson, T., Olsson, M. and Lundin, L. 1987. Soil improvements and intense forest production at a peatland. *Swedish University of Agricultural Sciences, Department of Forest Soils, Reports in Forest Ecology and Forest Soils, Report 58*, 51 p. (In Swedish, with English summary).

Nykvist, N. and Rosén, K. 1985. Effect of clear-felling and slash removal on the acidity of northern coniferous soils. *Forest Ecology and Management 11*, 157-169.

Nyrönen, T. 1995. Peat production and climate change. In: *Peat Industry and Environment*, Pärnu, Estonia, 12-15 September, 1995, 39.

Obernberger, I., Biedermann, F., Widmann, W. & Riedl, R. 1997. Concentrations of inorganic elements in biomass fuels and recovery in the different ash fractions. *Biomass and Bioenergy 12*, 211-224.

Ohno, T. 1992. Neutralization of soil acidity and release of phosphorus and potassium by wood ash. *Journal of Environmental Quality 21*, 433-438.

Ohno, T. & Erich, M.S. 1990. Effect of wood ash application on soil pH and soil test nutrient levels. *Agriculture, Ecosystems & Environment 32*, 223-239.

Olsson, B.A., Bengtsson, J. and Lundkvist, H. 1996. Effects of different forest harvest intensities on the pools of exchangeable cations in coniferous forest soils. *Forest Ecology and Management 84*, 135-147.

Olsson, M., Rosén, K. and Melkerud, P.-A. 1993. Regional modelling of base cation losses from Swedish forest soils due to whole-tree harvesting. *Applied Geochemistry, Supplement No. 2,* 189-194.

Olsson, T. 1990. Försöksstationen Sösdala – Försök med energiskog på organogen jord (utbruten torvtäkt). *Statens energiverk EO 90/3*, 81 p. (In Swedish, with English summary).

Paavilainen, E. and Päivänen, J. 1995. Peatland forestry: ecology and principles. *Ecological studies 111*, 248 p.

Parkman, H. & Munthe, J. 1998. Wood ash and dolomite treatments of catchment areas: Effects on mercury in run-off water. *Scandinavian Journal of Forest Research, Supplement No. 2*, 33-42.

Persson, H. & Ahlström, K. 1994. The effects of alkalizing compounds on fine-root growth in a Norway spruce stand in southwest Sweden. *Journal of Environmental Science and Health A29*, 803-820.

Piirainen, S. and Finér, L. 2000. Leaching from wood ash fertilized drained peatlands. *Proceedings of the 11th International Peat Congress, Quebec City, Canada, August 6-12, 2000, Volume II*, 977-983.

Podzharov, V.K. 1983. Reclamation of cut-away peat fields in the forestry of the Byelorussian SSR. *Proceedings of the International Symposium on Forest Drainage*, Tallinn 1983, 131-136.

Pohlandt, K. and Marutzky, R. 1993. Zusammensetzung und Eluierbarkeit von Aschen aus industriellen Feuerungsanlagen holzverarbeitender Betriebe. *Holz als Roh- und Werkstoff 51*, 193-196.

Ring, E., Lövgren, L., Nohrstedt, H.-Ö. & Jansson, G. 1999. Ash fertilization 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. *SkogForsk Report No.2, 1999*, 1-51.

Rowlands, R.G. & Feehan, J. 2000. Maximising the natural ecological potential of industrial cutaway peatlands in Ireland. *Proceedings of the 11th International Peat Congress*, Quebec City, Canada, August 6-12, 2000, Volume II, 679-683.

Saarela, I. 1991. Wood, bark, peat and coal ashes as liming agents and sources of calcium, magnesium, potassium and phosphorus. *Annales Agriculturae Fenniae 30*, 375-388.

Sallantaus, T. and Pätilä, A. 1985. Nutrient transport in runoff water from Finnish peatland drainage and peat mining areas. *Proceedings Peat and the Environment '85, Jönköping, Sweden, 17-20 September 1985*, 87-99.

Salonen, V. 1990. Early plant succesion in two abandoned cut-over peatland areas. *Holarctic Ecology 13*, 217-223.

Scheffer, B., Kuntze, H. and Bartels, R. 1981. Zum Phosphataustrag aus mit Gülle gedüngtem Hochmoorboden. *Landwirtschaftliche Forschung, Sonderheft 38*, 288-296.

Selin, P. 1996. Many uses for peatland cut-away areas. In: Vasander, H. (Ed.), *Peatlands in Finland.* Finnish Peatland Society, Helsinki, Finland, 128-129.

Selin, P. & Nyrönen, T. 1998. The use of cut-away areas in Finland. In: Malterer, T., Johnson, K. and Stewart, J. (Eds.), *Peatland Restoration & Reclamation – Techniques and Regulatory Considerations.* Proceedings of the international peat symposium, Duluth, Minnesota, 14-18 July, 1998, pp: 18-22.

Silfverberg, K. 1991. Wood ash, PK-fertilizer and two soil ameliorating additives on drained pine mires. *Suo 42*, 33-44. (In Swedish, with English summary).

Silfverberg, K. 1996. Nutrient status and development of tree stands and vegetation on ash-fertilized drained peatlands in Finland. D. Sc. thesis. University of Helsinki, Faculty of Science. *The Finnish Forest Research Institute, Research Papers 588*, 1-27.

Silfverberg, K. 1998. The leaching of nutrients from ash- and PK-fertilised peat. *Suo 49*, 115-123.

Silfverberg, K. and Huikari, O. 1985. Wood-ash fertilization on drained peatlands. *Folia Forestalia 633*, 1-25. (In Finnish, with English summary).

Silfverberg, K. and Hotanen, J.-P. 1989. Long-term effects of wood-ash on a drained mesotrophic Sphagnum papillosum fen in Oulu district, Finland. *Folia Forestalia 742*, 1-23. (In Finnish, with English summary).

Silfverberg, K. and Issakainen, J. 1991. Effects of ash fertilization on forest berries. *Folia Forestalia 769*, 1-23. (In Finnish, with English summary).

Someshwar, A.V. 1996. Wood and combination wood-fired boiler ash characterization. *Journal of Environmental Quality 25*, 962-972.

Staaf, H. and Olsson, B.A. 1991. Acidity in four coniferous forest soils after different harvesting regimes of logging slash. *Scandinavian Journal of Forest Research 6*, 19-29.

Steenari, B.-M. and Lindqvist, O. 1997. Stabilisation of biofuel ashes for recycling to forest soil. *Biomass and Bioenergy 13*, 39-50.

Stenbeck, G., 1985. Aspects on the reclamation of cut-away bogs. *Proceedings Peat and the Environment '85.* Jönköping, Sweden 17-20 September 1985, 165-174.

Tamm, C.O., Holmen, H., Popovic, B. and Wiklander, G. 1974. Leaching of plant nutrients from soils as a consequence of forestry operations. *Ambio 3*, 211-221.

Tammela, P.-T., Fredriksson, D. and Larsson, L.-E. 1996. Torvaska i kretslopp. *Stiftelsen svensk Torvforskning, Torvfakta 1-96*, 4 p. (In Swedish).

Thomas, P.A. & Wein, R.W. 1990. Jack pine establishment on ash from wood and organic soil. *Canadian Journal of Forest Research 20*, 1926-1932.

Thomas, P.A. & Wein, R.W. 1994. Amelioration of wood ash toxicity and jack pine establishment. *Canadian Journal of Forest Research 24*, 784-755.

Unger, Y.L. & Fernandez, I.J. 1990. The short-term effects of wood-ash amendment on forest soils. *Water, Air, and Soil Pollution 49*, 299-314.

Uosukainen, H. & Åman, P. 1999. Reindeer feed cultivation as latests stage of different uses of peatland in the Paarnitsa-aapa mire, Northern Finland. In: Halko, L. & Myllys, M.

(Eds.): *Chemical, Physical and Biological Processes in Peat Soils.* Abstracts from an International Peat Symposium, Jokioinen, Finland, 23-27 August, 1999, 116-117.

Valk, U. 1986. Estonian cut-over peatlands and their use in forestry. *Proceedings of the IPS Symposium Socio-economic Impacts of the Utilization of Peatlands in Industry and Forestry.* Oulu, Finland, June 9-13, 1986, 265-276.

Vance, E.D. 1996. Land application of wood-fired and combination boiler ashes: an overview. *Journal of Environmental Quality 25*, 937-944.

Vasander, H., & Roderfeld, H. 1996. Restoration of peatlands after peat harvesting. In: Vasander, H. (Ed.), *Peatlands in Finland.* Finnish Peatland Society, Helsinki, Finland, 143-147.

Veijalainen, H., Silfverberg, K. and Hytönen, J. 1993. Pulp biosludge and coal ash as nutrient sources for silver birch seedlings. *Suo 44*, 63-73. (In Finnish, with English summary).

Vestberg, M., Uosukainen, M., Kukkonen, S., Räkköläinen, M., Rahtola, M., Simojoki, P. 1999. Cultivation of horticultural crops on mined peat bogs. In: Halko, L. & Myllys, M. (Eds.): *Chemical, Physical and Biological Processes in Peat Soils.* Abstracts from an International Peat Symposium, Jokioinen, Finland, 23-27 August, 1999, 118.

Vikberg, P. 1996. Converting cut-away peatlands for game management purposes. In: Vasander, H. (Ed.), *Peatlands in Finland.* Finnish Peatland Society, Helsinki, Finland, 138-142.

Virkajärvi, P. & Huhta, H. 1996. Agricultural utilization of cut-away peatlands. In: Vasander, H. (Ed.), *Peatlands in Finland.* Finnish Peatland Society, Helsinki, Finland, 135-137.

Voundi Nkana, J.C., Demeyer, A. & Verloo, M.G. 1998. Chemical effects of wood ash on plant growth in tropical acid soils. *Bioresource Technology 63*, 251-260.

Westling, O. & Hultberg, H. 1990/91. Liming and fertilization of acid forest soil: short-term effects on runoff from small catchments. *Water, Air, and Soil Pollution 54*, 391-407.

Wheeler, B.D. & Shaw, S.C. 1995. *Restoration of Damaged Peatlands : With Particular Reference to Lowland Raised Bogs Affected by Peat Extraction.* HMSO, London. 211 p.

Williams, T.M., Hollis, C.A. and Smith, B.R. 1996. Forest soil and water chemistry following bark boiler bottom ash application. *Journal of Environmental Quality 25*, 955-961.

Zollner, A. and Remler, N. 1998. Eigenschaften von Holzaschen und Möglichkeiten der Wiederverwertung. *Forst und Holz 53*, 77-81.

Åman, P., Uosukainen, H. and Vertanen, H-K. 1998. Re-use of cut-off peatland areas: methods and cases in northern Finland. In: Malterer, T., Johnson, K. and Stewart, J. (Eds.), *Peatland Restoration & Reclamation – Techniques and Regulatory Considerations.* Proceedings of the International Peat Symposium, Duluth, Minnesota, 14-18 July, 1998, pp: 189-194.

Acknowledgements

First of all I want to thank my supervisor Prof. Mats Olsson and co-supervisor Lars Lundin for their support during all these years. For fruitful discussions and valuable comments on the manuscripts.

A number of persons have helped me to carry out the work in this thesis. I am very grateful to:

Bengt Lundén who was one of the initiators of forest experiments on the cutover peat area at Flakmossen. It was inspiring to work with you in the field. You were always cheerful and inspiring in spite of the sometimes awful weather in the field and I especially enjoyed your "Värmland"-stories.

Marie Bjurman, Kent Lindberg, Gunnel Legnerud, Gudrun Sunnerstrand, Ann-Marie Karlsson, Birgitta Eiritz, Eva Aasa, Lars-Erik Andersson, Kristina Bond, Lydia Haraldsson, Elice Axelsson, Berit Kindingstad, Maria Ahlgren, Maria Tillhammar, Eva Höglind and Kjell Larsson, who helped me with the field work, performed the laboratory work, and helped me with problems concerning field work and laboratory work.

Ronny Nyström, who performed the drainage and the application of fertilizers on the cutover peat area at Flakmossen. Birger Danfors at the Swedish Institute of Agricultural and Environmental Engineering, who placed the special rotovator at our disposal. Thure Sjödahl, Per-Åke Sköld, Peter Pettersson, Ulf Yxhammar, the kitchen staff and other members of staff at the agricultural school in Lillerud, who feed us, provided us with accommodation and helped us in the field work in many possible and impossible ways. Birger Jonsson, Sverker Rosell, Henning Karlsson, from the County Forestry Board in Värmland, who helped us with some practical forestry problems.

Alice and Helena Sjödahl, Peter Lundberg and Peter Hammarberg for field measurement of groundwater levels, temperature and runoff sampling, taking water samples and clearing weeds. Fritz Eriksson for making the vegetation inventories.

Maria Greger for fruitful discussions about heavy metals in bilberries. Hillevi Eriksson and Agnetha Alriksson for useful advice and valuable comments on manuscripts. Åke Nilsson, who helped me solving computer and statistical problems. Annika Lundberg and Kristina Lindström for all their organisational help.

All my colleagues at Department of Forest Soils for useful advice and discussions, but most of all for giving me many good laughs at the coffee breaks.

Anita Lundmark and Mary McAfee for correcting the English in the manuscripts.

My beloved sons: Marcus and Johan, thank you for your help and encouragement and most of all for your understanding that I, during the conclusion of this thesis, have been an absent-minded father not having time to share your problems with PC-games.

This work was financially supported by the Swedish National Board for Industrial and Technical Development and the Swedish Environmental Protection Agency.