WOOD ASH RECYCLING STATE OF THE ART IN FINLAND AND SWEDEN DRAFT 31.10.2003

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WOOD ASH RECYCLING – STATE OF THE ART IN FINLAND AND SWEDEN

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Summary

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In Finland and Sweden, large amounts of wood ash are generated annually in forest industry and energy plants. Especially in Finland, a great deal of the produced ash is mixed ash from co-combustion of several fuels, mainly wood and peat. Most of the ash is still dumped in industry's own landfills or transported to municipal landfills. Only less than 10% of the ashes are recycled into forests. However, as the costs of landfilling have risen, the need for recycling options for wood ash has become increasingly urgent.

The aim of this report is to present the state-of-the-art of wood ash fertilising in Finland and Sweden. The motivation behind wood ash recycling as forest fertiliser has been a bit different in these countries. In Finland, the aim has traditionally been to increase the tree growth in peatland forests. In Sweden, on the other hand, the main target has been to reduce the soil acidification in mineral soil forests. Both of these objectives can be reached with wood ash recycling.

The ash characteristics and impacts on soil and trees have been studied for many years both in Finland and Sweden. The recent studies have tried to find new options for ash processing and spreading to improve the competitiveness of ash fertilising and to decrease the problems caused by dusting and harmful components of ash. The main results of these studies are presented in this report.

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ABSTRACT

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PREFACE

In the Lombardia Region, Italy, a BIOCEN project has been started to support the regional target of promoting biomass energy. The main objective of the project is to develop the technical background for the assessment at local and regional level of a new regulation for the ashes distribution in particular in the forestry sector. As part of the BIOCEN project, a state-of-the-art study is being carried out to find out the current status of ash recycling in different European countries.

The aim of this report is to contribute the state-of-the-art study by providing information about Finnish and Swedish experiences on wood ash recycling. Wood ash has been used as fertiliser in experimental level for several years in these countries, even though the practice has not yet become common. The characteristics of wood fuels and wood-based ashes have been reported widely as well as the impacts of ash fertilising on soil chemistry and tree growth. The most recent studies have concentrated more on ash processing and spreading technologies to improve the competitiveness of ash fertilising and to decrease the problems caused by dusting and harmful components of ash.

The study has been carried out mainly as literature survey. In addition, many discussions have been carried out with several researchers for better insight into the subject. Especially, research scientist Saara Isännäinen from VTT Processes is acknowledged for valuable discussions and advice.

CONTENTS

1 INTRODUCTION

Forests have a significant role in Finnish and Swedish energy supplies. The predominant part of the energy from forests originates from industrial residues of stemwood but the extraction of branches and tops for energy purposes has also become common in many places. There is a considerable increase in the removal of nutrients when not only stemwood but also branches and tops are harvested in the ever-increasing exploitation of forests (NBF 2001). It is essential that these activities are conducted in such a way as not to put the requirements for the biological diversity of the forests at risk, or that the nutritive conditions in forest ground deteriorate or that conditions in ground water, lakes, watercourses or seas are impaired.

The most important tree species used as raw material in Finnish and Swedish forest industry are spruce (*Picea abies*), pine (*Pinus sylvestris*) and two birch species (*Betula pubescens* and *B. pendula*) (Taipale 1996). As most of the wood fuels used in energy plants are either industrial by-products or residues from raw material harvesting for industry, these are also the main species of wood fuels.

In Finland and Sweden, large amounts of wood ash are generated annually in forest industry and energy plants. Most of the ash is still dumped in industry's own landfills or transported to municipal landfills. The Finnish forest industry produces annually about 100 000 tonnes of wood ash (Vesterinen 2003). Only about 10% of this amount is being used as forest fertiliser. At the moment, the total recycling rate of the wood ashes from Finnish pulp and paper mills is about 30% - wood ash is also utilised in road construction and landscaping (Väätäinen et al. 2000).

In Sweden, about 11 000 tonnes of wood ash were recycled to forests in 2000 (Vesterinen 2003). This is less than 5% of the total amount of recyclable wood ash (see Table 1).

Table 1. The annual ash quantities in Sweden (Vesterinen 2003).

Source	**Amount (1000 ton/a)**	**Quality**
Energy plants	80 120 – 160 264	Recyclable wood ash Non-recyclable wood ash Other
Pulp and paper industry	98 – 130 130 – 170	Recyclable wood ash Non-recyclable wood ash
Sawmills	100	Recyclable wood ash

As the costs of landfilling have risen, the need for recycling options for wood ash has become increasingly urgent. In addition, a high-quality landfill is needed to avoid risks for the environment in longer term, due to potential leaching of compounds and their

drifting to surface and ground waters (Väätäinen et al. 2000). Thus, wood ash recycling would ease the continuously worsening waste problem.

Already when the traditional slash-and-burn farming method was introduced, it was known that wood ash improves growth, both in fields and in forests. Wood ash contains nutrients, which could be recycled back to forests for forest growing and ecological reasons. In Finland, especially wood ash recycling in peatlands has been studied a lot, and the results have shown strong and long-lasting impact on the growth. As an alkaline (pH 12 – 13) substance, ash decreases the soil acidity. In Sweden, the main motivation for ash recycling is the liming effect of ash which has been recognised in fertilising mineral soil. Therefore, ash is mainly used to prevent soil acidification, especially in Southern Sweden.

The aim of this report is to present the state-of-the-art of wood ash fertilising in Finland and Sweden. Ash recycling in road construction or landscaping is not treated in this context. First, the characteristics of wood fuels and wood ash are presented for the main tree species in Finland and Sweden. In chapter 3, the wood ash utilisation options in forestry and agriculture are presented. As an example, the experiments and main results of a Swedish study on recycling ashes from pulp industry are presented. Chapter 4 handles ash processing and spreading technologies used in Finland and Sweden. The related legislation and some recommendations are presented in chapter 5, and some safety aspects are handled in chapter 6. Finally, the main conclusions are drawn in chapter 7.

2 WOOD ASH CHARACTERISTICS

The characteristics of wood ash depend on the components of the wood fuel. The wood fuel characteristics, on the other hand, are affected by the tree species and part, soil nutrients and fertilising of the growing site, etc. Therefore, some main characteristics of different wood fuels are presented first, in chapter 2.1. After that, the special characteristics of wood ash are studied in more detail in chapter 2.2.

2.1 WOOD FUEL CHARACTERISTICS

The main components in a wood cell are cellulose, hemicellulose and lignin (Taipale 1996). These form 99% of the wood. In addition, wood contains some extractive agents, ash and minerals. In Nordic tree species (spruce, pine and birch) the share of cellulose is about 40% of the dry matter. Hemicellulose accounts for 25 – 30%. In softwood, the lignin content is 24 – 33%, in hardwood it is 16 – 25%. The share of extractive agents is normally less than 5%. The ash contains the minerals in wood. The share of these incombustible, inorganic compounds is usually less than one per cent of the weight.

The chemical structure of bark is somewhat different from that of wood. The shares of the compounds are different, e.g. the content of extractive agents is much higher. In birch bark, for example, the share of extractive agents is almost 40% (Taipale 1996).

The content of volatile compounds in wood is high (80 – 90%). The gasification of wood starts at 150 ˚C, is strongest at 300 – 450 ˚C and ends at 800 ˚C (Taipale 1996). Wood catches fire quite easily, due to the powerful gasification. The ignition point of dry wood is about 200 ˚C.

Compared to hard coal and peat, the energy content of wood is lower, which sets requirements to wood handling and combustion equipment. In Finland, the energy content per weight unit is almost the same for all tree species. However, birch has higher energy content per volume, because of higher bulk density. In addition, moisture content is essential in determining the energy content of a certain fuel batch.

The ash content is generally higher in bark than in stemwood. It can be even much higher, due to soil and sand from the fuel transport and handling phases. Of different parts of a tree, the highest ash content is in leaves and needles (Taipale 1996).

Wood has comparatively lower carbon content, higher oxygen content and much lower nitrogen content than other fuels. The hydrogen content is about the same. The inorganic compounds in wood originate from the soil nutrients.

In addition to low ash contents, the composition of wood ash is completely different from fossil fuel ashes. The stemwood and bark as compounds differ a bit from each other. There are also some differences between different tree species.

In the following tables, the average ash contents (Tables 2 and 3) and element contents (Table 4) of different wood fuels are presented, as well as the mineral and micronutrient contents in different parts of softwood and hardwood (Table 5).

Table 2. Average ash contents of different wood fuels (Taipale 1996).

Wood fuel	**Ash content in dry matter, w-%**
Chopped firewood	1.2
Whole tree chips, pine Whole tree chips, mixed species	0.6 0.5
Birch chips	0.4 – 0.6
Forest residue chips	1.3
Stump chips	0.5
Sawdust, with bark Sawdust, pine, without bark	1.1 0.08
Cutter chips	0.4
Pine bark	1.7
Spruce bark	2.3 – 2.8
Birch bark	1.6

Table 3. Contents of clean ash in fuel chips from newly felled small-sized trees (Taipale 1996).

Chip raw material	**Ash content in dry matter, w-%**				
	Birch	**Alder**	**Aspen**	**Pine**	**Spruce**
Delimbed stemwood	0.68	0.92	0.92	0.74	1.04
Whole tree, without leaves	0.79	1.08	1.09	0.80	1.25
Whole tree, with leaves	0.98	1.25	1.30	0.86	1.56

Table 4. Element contents in different wood fuels (Taipale 1996).

Wood fuel	**Element content, w-% in dry matter**					
	C	**H**	**N**	**O (margin)**	**S**	**Cl**
Whole tree chips, pine	51.8	6.10	0.30	41.19	0.01	0.0042
Forest residue chips	51.3	6.10	0.40	40.85	0.02	0.0076
Softwood chips					0.02 – 0.045	
Hardwood chips					0.02 – 0.09	
Sawdust, pine, without bark	51.0	5.99	0.08	42.82	0.00	< 0.0050
Willow (salix)	49.7	6.10	0.40	42.59	0.03 – 0.05	0.0037
Pine bark	52.5 – 54.5	5.7 – 5.9	0.3 – 0.4	37.7 – 39.65	0.03	0.0085
Spruce bark	49.9 – 50.6	5.9	0.4 – 0.5	40.2 – 41.43	0.03	0.0279
Birch bark	56.6	6.8	0.8	34.2		

Table 5. Mineral and micronutrient contents in different parts of softwood and hardwood (Taipale 1996).

Wood species/part	**Main mineral in dry matter, w-%**				**Micronutrient in dry matter, ppm**				
	P	**K**	**Ca**	**Mg**	**Mn**	**Fe**	**Zn**	**B**	**Cu**
Softwood:									
stem	0.01	0.06	0.12	0.02	147	41	13	3	2
bark	0.08	0.29	0.85	0.08	507	60	75	12	4
branches	0.04	0.18	0.34	0.05	261	101	44	7	4
needles	0.16	0.60	0.50	0.09	748	94	75	9	6
Whole tree	**0.03**	**0.15**	**0.28**	**0.05**	**296**	**85**	**30**	**6**	**4**
Hardwood:									
stem	0.02	0.08	0.08	0.02	34	20	16	2	2
bark	0.09	0.37	0.85	0.07	190	191	131	17	13
branches	0.06	0.21	0.41	0.05	120	47	52	7	4
leaves	0.21	1.17	1.10	0.19	867	135	269	21	10
Whole tree	**0.05**	**0.21**	**0.25**	**0.04**	**83**	**27**	**39**	**6**	**5**

As far as sulphur contents of softwood and hardwood are concerned, it can be stated that the contents are higher in leaves and needles, and lower in the stem (Table 6). In the whole tree, the differences between softwood and hardwood are very small.

Table 6. Sulphur contents in the dry matter of different parts of softwood and hardwood (Taipale 1996).

Wood species/part	**Sulphur content in dry matter**	
	ppm	**w-%**
Softwood:		
stem	116	0.0116
bark	343	0.0343
branches	203	0.0203
needles	673	0.0673
Whole tree	**236**	**0.0236**
Hardwood:		
stem	90	0.0090
bark	341	0.0341
branches	218	0.0218
leaves	965	0.0965
Whole tree	**212**	**0.0212**

It can be noted that according to Swedish studies the sulphur content of green pine and spruce needles is 0.07 – 0.11 w-% in dry matter basis. The sulphur content of brown needles is 0.03 – 0.08 w-% (Taipale 1996). In small branches the sulphur content in dry matter is 0.24 – 0.50 w-% and in other branches with bark it is 0.02 – 0.03 w-%. The same Swedish study found out that the sulphur content in stemwood is 0.01 – 0.02 w-%.

The metal contents vary based on e.g. soil conditions, tree species, different parts of the tree and metal load. However, in wood the metal content variations are smaller than in peat or hard coal. For most trace metals, the amounts in relation to the energy content are in average two to ten times lower than in peat (Taipale 1996). In bark and branches the metal contents are usually higher than in stemwood. The willow (salix) species have 5 – 10 times higher cadmium and zinc contents than other tree species. Both wood and bark have only very small amounts of actual heavy metals. Taipale (1996) has collected published information on some separate results about heavy metal contents in wood (Table 7).

Table 7. Heavy metal contents in different wood fuels and tree parts

Wood fuel/part	**Heavy metal contents in dry matter, mg/kg**								
	As	**Cd**	**Cr**	**Cu**	**Hg**	**Pb**	**V**	**Zn**	**Ni**
Wood fuel	0.04 – 0.4	0.1 – 0.4	1 – 2	0.6 – 6	0.01 – 0.02	0.6 – 14	0.3 – 5	5 – 40	
Branch, spruce		0.23	0.15	6.68		9.25		71.2	3.34
Bark				4.6				90	
Needle, spruce pine		 0.09 0.30	 0.06 0.08	 2.48 3.76		 0.30 1.25		 14 65	 1.62 1.45
Leaf, birch		0.30	0.08	3.76		1.25		65	1.45
Willows		0.8 – 1.7	3	2 – 5		0.4 – 2		40 – 105	

2.2 WOOD ASH CHARACTERISTICS

The growing site of a tree has a great influence on the wood fuel characteristics. In addition to the soil type and fertilising measures, also different heavy metal deposits etc. impact on the fuel contents, thus impacting the ash characteristics as well. For example, it has been noticed that the wood ash from forest industry plants in Eastern Finland contain more heavy metals than those from other parts of Finland. This is probably a consequence of using more Russian stemwood as industrial raw material near the eastern border.

Wood ash consists of the inorganic substances of wood. Typical elements in wood ash are silicon (Si), calcium (Ca), potassium (K), phosphorus (P), manganese (Mn), iron (Fe), zinc (Zn), sodium (Na) and boron (B) (Taipale 1996). The most common element in wood ash is clearly calcium, potassium being the second most common.

The components of stemwood ash and bark ash differ a bit from each other. There are also some differences between tree species. Stemwood ash contains more potassium and magnesium oxides than bark ash. On the other hand, bark ash contains plenty of silicon. Because of its high contents of minerals and micronutrients which are essential for the nature, wood ash is recommended to be returned into the natural cycle (Taipale 1996).

The element contents of some wood fuel ashes have been collected in Table 8. Table 9 presents the shares of some elements in stem ash from newly felled small-sized trees. With newly felled trees, the nutrients have not been leached during the storing.

Table 8. Shares of the main elements in some wood fuel ashes (Taipale 1996).

Wood fuel	**Element percentage in ash dry matter, w-%**									
	Ca	**Na**	**Al**	**Fe**	**Ti**	**Mg**	**K**	**Si**	**S**	**P**
Whole tree chips, pine	24	0.16	2.70	1.50	0.034	3.10	10	11	0.65	2.10
Forest residue chips	11	0.26	2.50	2.60	0.30	2.40	6.90	18	0.65	1.40
Sawdust, pine	29.9	0.20	1.06	1.29	0.070	7.12	10.2	3.90	0.78	2.29
Spruce bark	28	0.28	0.57	0.10	0.021	3.10	6.30	0.70	0.39	1.80
Pine bark	29	0.37	2.80	0.21	0.046	2.70	6.30	0.60	0.82	2.10
Willow (salix)	22	0.20	0.16	0.13	<0.01	3.10	22	0.02	1.20	5.00

Table 9. Shares of some elements in stem ash from newly felled small-sized trees (Taipale 1996).

Tree species	**Element percentage in ash, w-%**									
	P	**K**	**Ca**	**Mg**	**Mn**	**Fe**	**Zn**	**S**	**B**	**Cu**
Birch	4.3	16.4	20.8	4.1	1.1	0.6	0.5	1.8	0.05	0.04
Alder	5.8	19.3	19.3	2.9	0.7	0.6	0.3	2.3	0.05	0.05
Aspen	1.9	21.4	20.9	3.2	0.5	0.5	0.2	1.8	0.06	0.03
Spruce	2.7	12.3	24.5	3.0	3.3	0.7	0.3	1.3	0.05	0.04
Pine	2.2	11.5	22.2	5.1	2.1	0.7	0.2	2.8	0.05	0.03

Wood ash consists of oxides of several elements, silicates and nitrates. The main component in wood ash is CaO. The composition of some wood fuel ashes as the oxides of the main components is presented in Table 10. Because of its composition, wood ash is very alkaline, its pH is 12 (Taipale 1996).

Table 10. Ash composition (w-%) of some wood fuel ashes, as oxides of the main components (Taipale 1996).

Tree species	Percentage in ash, w-%									
	CaO	**K_2O**	**P_2O_5**	**MgO**	**Fe_2O_3**	**SO_3**	**SiO_2**	**Na_2O**	**Al_2O_3**	**TiO_2**
Birch*	57.8	11.5	7.7	7.7		3.8	3.8	7.7		
Birch*	46.0	15.0	14.9	11.6	1.3	2.6	0.9	8.6		
Pine	42.0	15.2	1.0	16.0	5.5	4.5	4.6	3.0		
Spruce	36.7	29.6	1.0	10.0	8.5	4.2	1.0	3.2		
Willow	30.8	26.5	4.8	5.1	0.2	2.1	0.43	0.3	0.3	0.02
Sawdust, pine	41.8	12.3	5.2	11.8	1.9	1.9	8.3	0.2	2.0	0.1

* Two values were provided in the source

In Finland and Sweden, bark is an important wood fuel, as the amounts of bark by-products in forest industry are significant. Therefore, some separate studies have been carried out concerning the composition of bark ash. The bark ash content and composition of different tree species is presented in Table 11.

Table 11. Ash content and compounds in bark of different tree species (Alakangas 2000).

Tree species	Ash, %	Percentage in ash, w-%								
		SiO_2	**Fe_2O_3**	**P_2O_5**	**CaO**	**MgO**	**Na_2O**	**K_2O**	**SO_3**	**Other***
Pine	1.8	14.5	3.8	2.7	40.0	5.1	2.1	3.4	3.7	22.9
Spruce	3.4	21.7	1.8	2.7	50.5	4.2	2.8	3.5	1.6	7.8
Birch	1.6	3.0	1.0	3.0	60.3	5.9	0.7	4.1	4.8	15.6
Oak	1.5	11.1	3.3		64.5	1.2	8.9	0.2		9.3

* Calculated as a difference

The amounts of heavy metals in power plant ashes vary a lot. The differences may be greater between different wood fuels than between different biofuels (Taipale 1996). One reason for this is naturally differences in the combustion and flue gas cleaning efficiencies in power plants. Table 12 presents the results of a Swedish study concerning heavy metals in bottom and fly ash from wood combustion. Ashes of wood based fuels have harmless heavy metal contents, unless significant amounts of coal or oil ashes are mixed with the wood ash. However, it would be wise to avoid ashes of demolition wood, waste paper or other such source.

Table 12. Heavy metal contents in bottom and fly ash from grate combustion of wood (Taipale 1996).

Element	**Element content, mg/kg**	
	Bottom ash	**Fly ash**
Arsenic (As)	0.2 – 3	1 – 60
Cadmium (Cd)	0.4 – 0.7	6 – 40
Cobalt (Co)	0 – 7	3 – 200
Chromium (Cr)	– 60	40 – 250
Copper (Cu)	15 – 300	200
Mercury (Hg)	0 – 0.4	0 – 1
Manganese (Mn)	2500 – 5500	6000 – 9000
Nickel (Ni)	40 – 250	20 – 100
Lead (Pb)	15 – 60	40 – 1000
Selenium (Se)		5 – 15
Vanadium (V)	10 – 120	20 – 30
Zinc (Zn)	15 – 1000	40 – 700

3 ASH UTILISATION OPTIONS

In practice, the wood ash to be used in forest fertilising comprises of fly ash from fluidised bed boilers of forest industry. This is due to the fact that the fly ash volumes are much greater than that of bottom ash. In addition, the quality of bottom ash is too coarse and difficult to handle. Most of the impurities in fuel are left in the bottom ash and the treatment would probably be too expensive compared to the volumes to be reached.

3.1 USE AS FOREST FERTILISER

The good fertilising effect of wood ash on pine growth on nitrogen rich peatlands has long been known as the result of the earlier studies that were started by the Finnish Forest Research Institute in 1930's (Korpilahti et al. 1998). The fertilising effect of ash depends mainly on its phosphorus, potassium and boron content. Ash dies not increase tree growth on mineral soil because it does not contain nitrogen, which is lacking in mineral soil. Despite of its positive impacts on peatland forests the use of ash has remained on experimental level. Pre-treatment methods were not known and only dry, dusty ash has been available. Compared to artificial fertilisers, much bigger amounts of wood ash should be applied to get growth responses (4 – 5 tons of wood ash per hectare compared to about 0.5 tons of fabricated fertiliser).

The fertilising effect of wood ash normally lasts for 30 – 40 years (Väätäinen et al. 2000). With fabricated fertilisers with the same phosphorus and potassium content, the fertilising effect has been estimated to last for 15 – 25 years. Wood ash contains right proportions of all nutrients except nitrogen, which are required for tree growth. In addition, wood ash has proved to be a good health fertiliser: with wood ash fertilising, nutrient-based dysmorphism has been decreased and even cured in peatlands and field forestation areas.

The results of the first fertilisation trials started in 1930's on drained peatlands showed that ash increases tree growth and improves the natural stand regeneration (Korpilahti et al. 1998). The early studies also showed that ash fertilisation accelerated the activity of micro-organisms in the surface peat. Later studies have supported these findings and confirmed that the effects are long-lasting. The growth of pine (*Pinus sylvestris*) has increased on the nitrogen rich sites where the total nitrogen content in the surface peat layer is 1.5 – 2.5% of dry weight. On nitrogen poor sites where the peat nitrogen is < 1%, the increase of tree growth has remained low. The respond of tree growth to ash fertilisation is slower than to the commercial phosphorus-potassium fertilisers, but after ten years of ash fertilisation the growth has been similar or even better when equal amounts of nutrients have been applied. Peatland forests fertilised with wood ash have not shown growth disturbances or trace element deficiencies; on the contrary wood ash has corrected such disturbances in short time. The effect of wood ash fertilisation has lasted in some nitrogen rich sites 30 – 50 years averaging from three to four cubic meters additional yield per year (Korpilahti et al. 1998). However, if the ash dosing is

less than 2 t/ha, no notable effect on growth or plant nutrient balance was noticed (Väätäinen et al. 2000).

Phosphorus is often the most important growth restricting nutrient in peatlands (Väätäinen et al. 2000). Therefore the basis for dosing in ash fertilising is normally the phosphorus content in ash. If ash fertilising is aimed at the recommended one-shot dosing (45 kg P/ha), the ashes with variable qualities should be spread with variable dosing per hectare. Based of the analyses of ashes from forest industry, showing the average phosphorus content of a bit less than one per cent (8.1 g/kg) of the total nutrient content in wood ash, it can be said that the minimum dosing of ash should be at least 5 t/ha. It needs to be noted, that ash treatment and storing methods impact on the nutrient contents, so that ash moisturising and outdoors storing cause nutrient losses.

Wood ash fertilisation has not increased tree growth on mineral soils because it does not affect the nitrogen supply available to trees. In some cases it has even decreased tree growth on mineral soils. Ash fertilisation has a strong liming effect, it rises the pH value and increases the amounts of nutrients (P, K, Ca, trace elements) in the surface soil both on peatlands and mineral soil sites (Korpilahti et al. 1998). Also the activity of microbes increases and the decomposition of litter speeds up. On mineral soil sites ash fertilisation can compensate the nutrient losses caused by harvesting operations, nutrient leaching and soil acidification. Thus even without tree growth increase the effects of ash fertilisation can be seen to be positive.

When wood is burning, the heavy metals are enriched into the ash. Of these, cadmium has been seen as the most harmful. The studies so far have shown, however, that ash fertilising does not cause exceeding limit values in berries (Väätäinen et al. 2000). Also the heavy metal leaching into surface and ground waters has been insignificant. When fertilising with ash, it is important to know beforehand its composition, so that the heavy metal contents do not exceed the limits. Large-scale ash fertilising in forests also requires more information acquisition about the environmental effects of ash.

At present, reliable methods to characterise ash with regard to the speed of dissolution in the field are missing (NBF 2001). One way of estimating the stability of finished ash product (e.g. granules or pellets) is to measure the conductivity in water extracts in accordance with the reactivity analysis method described in Chapter 3.3. This gives a total measurement of the dissolution of salts from the ash and indicates the risk of acute damage to vegetation, especially mosses and lichens. If the guiding values, given in Table 13, are exceeded for one ash product, the effects on ground vegetation should be examined more stringently before the product is spread on a larger scale.

Table 13. Preliminary target values in the judgement of ash products in Sweden (NBF 2001).

Dosage	**Conductivity**
1 ton/hectare	14 mS/cm
2 tons/hectare	12 mS/cm
3 tons/hectare	10 mS/cm

Another way to judge the characteristics of a product in the field is to use a method for leaching wood ash (NBF 2001). This method demonstrates a conceivable process in the field with regard to the acid-neutralising ability of ash and the release of nutritive substances. The method can be an aid with regards to comparing various products and working out routines for the production of compensatory fertilising agents. The method is based on the repeated leaching of ash products in a laboratory environment and indirectly describes the long-term leaching process in natural conditions. The leachate corresponds to several decades of leaf-fall in the field.

3.2 USE IN AGRICULTURE

In Finland, agricultural use of wood ash has not been possible, because the cadmium content of wood ash usually exceeds the allowable limit (Korpilahti et al. 1998). The Finnish limit values for heavy metal contents in crop fertilisers are presented in Table 14. These limit values apply only in agricultural use of fertilisers, not in forest fertilising.

Table 14. Limit values for heavy metal contents in field spreading, mg/kg (Isännäinen & Huotari 1994).

Heavy metal	**Limit value, mg/kg**
Mercury	2
Cadmium	3
Nickel	100
Zinc	1500
Copper	600
Lead	150
Arsenic	50

According to some studies, the cadmium contents of bottom ash are below the limit value of 3 mg/kg. However, the other quality properties and amounts of bottom ash are not sufficient for use in agriculture.

3.3 QUALITY CONTROL AND CHEMICAL ANALYSIS METHODS

When deciding upon the utilisation of ash or ash product, it is necessary to know the characteristics of the ash. To be able to compare the ash properties with the limit values, uniform analysis methods should be used for comparable results. In this chapter, the Swedish recommendations for ash quality control and chemical analysis methods are presented. The recommendations have been provided by Skogsstyrelsen (NBF, the National Forestry Board; NBF 2001).

3.3.1 Sampling

Sampling is to be conducted using a finished product but can, however, also be best conducted prior to processing, that is to say using incoming ash. Sampling should be carried out in accordance with the guidelines given in the Nordtest Method NT ENVIR 004 for the sampling of solid waste particles or SS 18 71 13 for biofuel and peat. Generally, sampling for analysis should take place for amounts of 250 – 500 tons of ash or finished ash product, or at least once during the period (i.e. autumn to spring) when forest fuel is burnt. In larger incineration plants and plants that use pure forest fuel, sampling can be carried out less frequently than in plants using a greater variety of fuels and with different operational conditions.

Sampling should be carried out by using at least 15 constituent samples, each of which comprising 1 litre so that they represent the finished product as well as possible. The constituent samples are to be carefully mixed to form a general sample. The number of constituent samples and their size will depend upon the homogeneity of the ash. More constituent samples will be required if the ash is evidently not homogeneous.

It is advantageous to take constituent samples from a conveyor belt or a falling discharge. When taking samples from piles, the constituent samples must be obtained from various heights and depths in the piles.

Reference samples, from every general sample taken from the finished product, should be saved for at least three years together with its analysis value. It must be noted that hardening during the time in storage can impair the reactivity of the reference samples.

3.3.2 Chemical analyses

Chemical analyses ought to be conducted by accredited laboratories. The following analytical methods are recommended:

Total contents of macro nutritive substances and trace elements

The target values for contents of macro nutritive substances and trace elements given in table 27 (Chapter 5) refer to total contents.

The following standard methods are recommended:

A. Decomposition in a lithium metaborate fusion; analysis ICP-AES (ASTM 3682).
B. Decomposition in HNO_3 + HCl + HF; analysis ICP-AAS, ICP-QMS (ASTM 3683).

The analyses can be used for practically all metals and phosphorus. Boron cannot be analysed using Method A. Volatile substances are analysed after decomposition in sealed containers.

Total contents comprise both easily dissolvable as well as sparingly soluble fractions. The methods can, therefore, overestimate the value of the ash product as a source of potassium if it contains a lot of sintered material or inert bed material. Moreover, the accessibility of certain heavy metals is lower than the total analyses indicate.

Content of extractable macro nutritive substances and trace elements

At present, research and development is underway into methods of characterising ash products with regard to availability of plant nutritive substances and noxious metals. The analysis of the potassium-nitrate-soluble fraction is recommended as an approximate measure of the substances that can be released during a forest generation process. This method can be employed as a complement to total analyses, especially for bottom ash or other ash suspected of containing inert material.

The method entails extraction in hot, concentrated (65%) nitric acid on a plate or in sealed Teflon containers in microwave ovens and following ICP-AAS. It can be used for the analysis of Ca, Mg, K, B, P, Cu, Zn, Mo, Co, Pb, Cd, As, Cr, Ni and V. Extraction in sealed containers is required for the analysis of Hg.

Total polyaromatic hydrocarbons (PAH)

Analysis is recommended to be carried out using HPLC or GC-MS after extraction in acetone/hexane or the equivalent. The total PAH is counted as the sum of 16 compounds (EPA 16).

3.3.3 Reactivity

Measurement of conductivity in water extracts

50 grams of finished ash product is mixed with 200 ml of deionised water (weight ratio 1:4) and shaken in a shaking machine for one hour. After sedimentation in the end vessel after 15 – 30 minutes, the conductivity and pH is measured in the clear solution.

Leaching of wood ash

The leaching of an ash product using a leaching liquid comprising deionised water that has been set at pH 4.0 (mixture ratio 1:2000): the leaching liquid is decanted after 24

hours and new liquid is added. The decanted liquid is analysed. This procedure of replacing liquids is continued for 30 days.

3.4 SWEDISH STUDY: RECYCLING OF ASHES FROM PULP INDUSTRY

In the following, some results from a Swedish study on ash recycling are presented. The study included two experiments with different doses of wood ash. The following information is based on a single source (SkogForsk 2000). This material was given to a Finnish group of ash researchers during their study tour and visit to two experiment sites (no. 249 and 250).

The greater part of the wood ashes generated today in Sweden comes from the pulp industry (about 100 000 tonnes per year). Today (situation in 2000) these ashes are landfilled. The aim of the project was to study the biological effects of bringing these ashes back to forest stands on mineral soil. The project was co-funded by the forest industry, the Swedish National Energy Administration and SkogForsk's (the Forestry Research Institute of Sweden) framework agreement.

3.4.1 Experiments

Design and treatments

The treatments were randomised within three blocks. In experiment no. 249 the grouping into the different blocks were primarily based on the soil water chemistry, while in experiment no. 250 it was primarily based on tree stand data. The treatments at these experiment sites are presented in Table 15.

Table 15. Treatments in experiment sites 249 and 250 Riddarhyttan (SkogForsk 2000).

1	Untreated control	
2	3 ton crushed ash per ha (dry weight)	
3	6 ton crushed ash per ha (dry weight)	
4	9 ton crushed ash per ha (dry weight)	
5	3 ton crushed ash per ha (dry weight)	+ 150 kg N[1] per ha; simultaneous application
6	3 ton crushed ash per ha (dry weight)	+ 150 kg N[1] per ha; application of the ash after the dissolvement of the N-granules
7	150 kg N[1] per ha	
8	3 ton pelletized ash per ha (dry weight)	
9	VNP[2] (corresponding to 150 kg N per ha)	
10	VNP[2] + 3 ton crushed ash per ha	

[1] N applied in the form of ammonium nitrate with lime (N 27.5%, Ca 4.0%, Mg 1.0% and B 0.2%)

[2] VNP = "Växtnäringspellets", i.e. pelletized mix of compost and sewage sludge

The wood ashes used

The crushed ash originated from ASSI-Kraftliner mill in Piteå. The ash was moistened and allowed to harden (see chapter 4.1) during one summer month before being crushed and screened. (During the hardening process the very reactive oxides and hydroxides in the ash are converted to carbonates or, under certain circumstances, to other compounds.) The formed ash particles were seemingly hard and compact. A later laboratory test showed, however, that the curing process had been incomplete. The crushed ash was easily dissolved in water and quite reactive.

The pelletized ash originated from Ortviken paper mill. During the pelletizing process, 8 – 10% of tall oil was added as binding agent. Table 16 summarizes the elemental concentrations of the ashes used in the experiments. The site and stand descriptions of the experiments are presented in Table 17.

Table 16. Elemental concentrations of the wood ashes used in the experiments. Figures in bold indicate relatively high values.

	Crushed ash (mean of 4 samples)	**Pell. ash** (mean of 2 samples)	**Normal interval**	**Rec. max** (3 ton dose)
Water content, %	26.3	13.9		
LOI, %	8.7	**33.6**		
Macro elements, concentration, % (ts)				
Ca	13.7	15.2	10 – 30	
Mg	1.4	1.4	1 – 3	
K	**6.4**	3.5	3 – 6	
P	0.8	0.8	0.1 – 1.3	
Al	1.9	3.1	1 – 3	
Mn	0.8	1.0	0.5 – 2	
S	0.5	0.3	0.1 – 1.5	
C	2.0	21.6		
Si	5.6	9.4	5 – 20	
Trace elements, concentration, ppm (ts)				
As	9.3	**15.2**	5 – 20	(15)
Pb	108	70	15 – 3 000	300
Cd	**11.7**	**9.4**	1 – 40	15
Cu	108	104	15 – 300	200
Cr	56.1	54.1	15 – 250	100
Ni	**114**	39.2	20 – 250	(100)
Zn	**3360**	**3990**	15 – 10 000	4 000
V	**76.6**	37.0	10 – 120	(50)
Hg	0.28	0.87	0.1 – 1	1.5

Table 17. Site and stand descriptions of the experiments.

	No. 249	**No. 250**
Latitude	59˚48’	59˚48’
Longitude	15˚30’	15˚32’
Altitude (m asl)	180	135
Annual precipitation (mm/a)	730	730
Yearly mean temperature (˚C)	3.9	3.9
Soil texture	sandy-silty till	medium coarse sand
Tree species	pine/spruce	pine
Site index (H_{100}, m)	T28	T24
Stand age (year)	60	50
Stem volume (m^3/ha)	195	150
Stems (pieces per ha)	475	1100
Stem mean height (m)	20	16

3.4.2 Results

Soil

The total carbon and nitrogen concentrations of the soil were representative for forest mineral soils in this region. The higher C and N concentrations in experiment 249 are in accordance with the differences in site fertility between the two sites. The total C and N concentrations in soil are presented in Table 18.

Table 18. Total carbon and nitrogen concentrations in soil (mean of three control plots).

Variable	**Horizon**	**No. 249**	**No. 250**
C (%)	humus mineral soil 0 – 7.5 cm mineral soil 7.5 – 15 cm	39.1 1.72 1.59	37.0 1.68 0.83
N (%)	humus mineral soil 0 – 7.5 cm mineral soil 7.5 – 15 cm	1.27 0.07 0.07	1.14 0.06 0.04
C/N	humus mineral soil 0 – 7.5 cm mineral soil 7.5 – 15 cm	30.8 24.4 21.6	32.5 26.7 22.4

One year after treatment, all three doses of crushed wood ash resulted in significant increases of the soil pH (Table 19). No effect of the pelletized ash could be seen.

Table 19. pH (H_2O) in the humus layer, one year after the treatment. Mean of three replicates.

Treatment	**pH**
Control	4.29a
Crushed ash, 3 ton	4.78b
Crushed ash, 6 ton	5.08b
Crushed ash, 9 ton	5.02b
Pelletized ash, 3 ton	4.32a

Soil water chemistry

Effects on the soil water chemistry, at 50 cm depth in mineral soil were observed during the first two years after treatment, using suction lysimeters type Prenart Super Quartz. They were mainly confined to variables of minor environmental significance, such as electric conductivity and concentration of Na. Of the analysed heavy metals, there was a tendency of an increased Cd-concentration in all treatments, and statistically significant in the treatments 150 kg N, 6 and 9 tons of crushed ash. On one occasion, 7.5 months after treatment, As, Cr, Zn, Ni and V were tested without any significant effects noted.

The ash treatments did not significantly effect the soil water pH, nor the concentration of inorganic N, phosphate-P and Al.

Notable is, that even the poorly hardened and rather reactive crushed ash used in this experiment, did not cause more significant effects in soil water – during the first two years after treatment and in doses up to 3 tonnes per ha.

The N-fertilisation on the other hand did cause high concentrations of inorganic N and Cd in the soil water. There was also a tendency, however not statistically significant, towards an increasing Zn concentration. A high amount of the supplied N was calculated to have leached out from the root zone. The fertilisation being made in late autumn is likely to cooperate in causing the high leakage of N, Al and Cd – an indication that performing of practical forest fertilisation should be finished somewhat earlier than today's practise.

Effects on forest yield

The observation period (four years) was too short to give any clear answers. However, callipering data from these first four years indicate a reduced tree stem growth on ash treated plots. For better estimation of the tree-growth effects, tree-height measurements and increment cores will be sampled.

Needle chemistry

Ash application increased concentrations of a number of nutrient elements in current needles. These increases may be a result of the nutrients added with the ash, as well as an effect in stimulating microbiological mineralization of soil organic matter.

Effects on the field and bottom layer vegetation

Nine months after treatment, extensive damage to the ground vegetation, particularly the bryophytes, was registered on all plots treated with crushed ash. No visible damages were found on the lichens. *Dicranum polysetum* was the species most susceptible to "burning" damage by ash treatment. Even at the lowest dose (3 ton/ha), only 10% of *D. polysetum* was undamaged. The pelletized ash caused no visible damages. Two years after the treatment the coverage of the bryophytes tended to recover, and after five years no visible damages could be found.

The "burning" effect on bryophytes (discoloration of the leaves) has been observed in several investigations with treatments with wood ash, lime, acids and N-, P- and K-fertilisers. However, it is not clear what chemical property of the ashes caused the negative impact in this study, since both high pH and high concentration of neutral K and P salts could be the cause.

The observations after five years imply that the treatments may cause some long-term effects on individual species and possibly change the species composition more permanently. There was also a statistically non-significant ($p > 0.05$) tendency of a decreased coverage of *Vaccinium myrtillus* on the plots treated with wood ash.

4 ASH PROCESSING AND SPREADING TECHNOLOGIES

4.1 PROCESSING TECHNOLOGIES

The transportation of loose ash requires much space, the ash handling is unclean, and the spreading accuracy and evenness are not good (Väätäinen et al. 2000). Moreover, ash dust erodes machine parts and may cause health risks. For large scale utilisation of ash, some kind of processing is required to avoid these problems.

The aim of the pre-treatment of ash is to compact or granulate ash more or less in order to avoid dust problems during transportation and spreading (Korpilahti et al. 1998). In Sweden active research of pre-treatment techniques and different aspects of ash recycling started in the beginning of 1990's, and the results achieved gave good contribution to the start of the latest Finnish studies. One possibility for processing ash and other forest industry by-products for fertiliser use is presented in Figure 1.

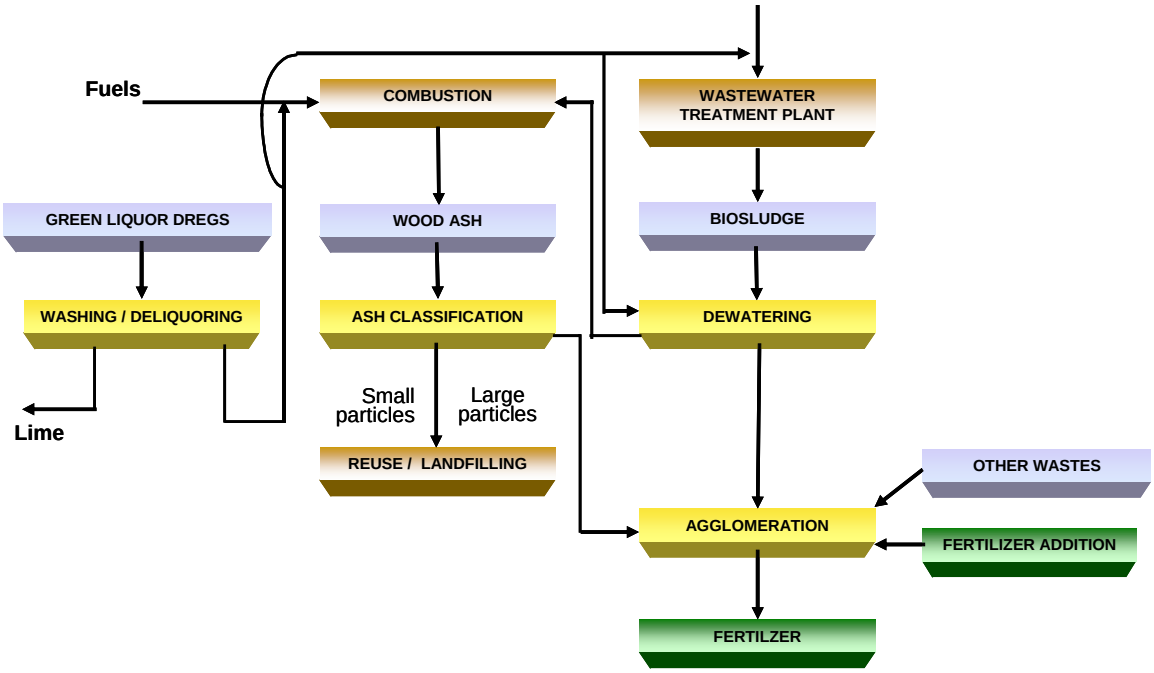

Figure 1. Processing of forest industry by-products for fertiliser use.

Two major forest companies in Finland have already had some experiments on ash granulation with drum and disc equipment (Korpilahti et al. 1998). On the other hand, Swedish experiments have suggested that the so-called self-hardening procedure might be a simple and successful method to process large quantities of ash, as is the case at pulp mills.

Recent studies in Finland have considered granulating wood ash together with biosludge to find a common solution for two difficult waste streams in pulp industry. Also different ash classification methods have been studied, aiming at reduced heavy metal contents in the ash fractions to be recycled.

The pre-treatment with water increases the moisture content of ash. In self-hardened ash there has been 20 – 30% of water, 40 – 50% in ash damped with sludge, and 12% in granules (Korpilahti et al. 1998). Ashes treated with different procedures differ also by other characteristics.

4.1.1 Self-hardening

In some power plants in Finland and Sweden, ash self-hardening has proved to be a low-cost method for ash processing (Väätäinen et al. 2000). In this method, ash is moisturised with water (about 30 – 40%) and the moist ash is transferred to storage area for hardening. The ash is moisturised with a separate screw moistener. Depending on the temperature, the hardening time may be 7 to 14 days, after which the ash starts to harden. Before spreading to forest, the hardened ash is screened and the biggest pieces are crushed if needed. The particle size varies from dust to some centimetres. The density of self-hardened ash varies between 700 – 800 kg/m^3 and its moisture content is about 25%. Self-hardened ash contains also some fine matter, so the dusting problem does not completely disappear.

In a recent ASH-project (Korpilahti et al. 1998), VTT Energy has carried out laboratory tests to experience how to mix water with dry ash and to find out the dependence of ash hardening on moisture content. It was found that the hardening process is very fast and the particles reach their “final” degree of hardness in a couple of days. The hardness of granules seemed to be at the maximum when water was added to the moisture content of 34 – 35%. Even the share of small, dusty particles decreased essentially towards this moisture.

Self-hardening was tried in full scale at Oy Metsä-Botnia Ab’s Äänekoski pulp mill in Central Finland (Korpilahti et al. 1998). They already had a mixing device with a double screw, which needed only some modification for controllable damping of ash. Fly ash is stored into a silo, the volume of which is 100 m^3. Ash is conveyed with a rotating gate and feeding device from the silo into the damper-unit. Altogether 12 nozzles are used to spray water. The production of ash is 10 – 12 tons (dry substance) per day and the silo is emptied once or twice a week. The temperature of ash is about 80 ˚C and when the hardening reaction releases heat, temperature increases to over 100 ˚C after adding water. According to an experiment carried out during the winter 1997 – 1998, the temperature decreased rather slowly during storage, which suggests that self-hardening procedure can be used year round. That was later confirmed in practical operations.

At the M-Real Savon Sellu fluting mill, industrial biosludge is used in ash moisturising instead of water (Kuusela 2003). The share of sludge in the self-hardening mixture is 25 – 35%. Because of the sludge, the hardened ash does not freeze even in wintertime.

A Swedish study (Ring 2002) revealed that self-hardened and crushed ash was very soluble, which was manifested in increased electrical conductivity and increased concentrations of mainly Na, K, Ca and SO_4^{2-} in the soil solution at about 50 cm depth. Heavy metals were not released to the soil solution at highly detrimental rates in the short term even at a dosage of 9 t/ha of this soluble ash. Nevertheless, an increased availability of Cd was observed, which needs to be considered at large-scale fertilisation. The effects on soil-solution chemistry as a whole at the two highest dosages with crushed ash (6 and 9 t/ha) were not considered as beneficial, whereas the effects at a dosage of 3 t/ha were more acceptable. The pelletized ash had better solubility properties than the crushed ash, since the pelletized ash seemed to dissolve at a rate compatible with the exchange rate of the soil. All ash treatments had minor effects on soil-solution pH. A simultaneous application of 150 kg N and 3 t crushed ash per hectare seemed to have increased the formation of NH_3. Fertilisation with 150 kg N/ha alone tended to give the highest Cd, Al and Zn concentrations compared with all other treatments, probably because of increased soil-solution acidity.

When the total investment costs for the necessary equipment and assembly for ash self-hardening are about 50 000 € and the operation does not require additional employers, the costs of the mere moisturising with ash production of 4 000 t/a are about 2.5 €/t (Väätäinen et al. 2000).

4.1.2 Granulating

If the whole logistics chain of ash recycling is considered, the best option for loose ash treatment could be to process it into a form, which is as alike as possible with artificial fertilisers (Väätäinen et al. 2000). Ash granulation could be a solution to several ash recycling problems that appear with loose ash. Because of its high weight by volume (900 – 1100 kg/m^3), the capacity of the transport capacity of the machinery can be well utilised, which decrease the treatment costs per ton.

There are very few fine particles in granulated ash, so dust problems and their consequences can be avoided. The dosing and spreading are easier, more even and more easily adjustable with granulated ash than with dust-like matter (Väätäinen et al. 2000). Compared with loose ash, granulated ash has wider effective width in spreading. Well-stored granulated ash is homogenous, which decreases blocks in distributor during the spreading.

Ash granulating can be implemented using several methods. These include plate, drum and rolling granulation methods (Väätäinen et al. 2000). At Enocell Oy Uimaharju mills, Enotuhka Oy has produced granulated ash with plate granulation method since 1997. The equipment has been delivered by Tecwill Oy, which manufactures concrete stations as the main product. The ash granulating station is based on equipment and components of concrete granulating, adapted for the specific needs of ash granulation. In granulating process, loose ash and water are weighted and moisturised with a pan mixer. The ash-water mixture is fed into a rotating plate, which is about three meters in diameter and set in inclined position. During the treatment, the mixture shapes into granulated form. The moisture content of the resulting ash granules is about 12%. The

particle size of the granules from plate granulation can vary a lot. If more homogenous ash granules are needed, the smaller ones can be returned to the process and the bigger ones can be crushed.

The investment costs of the Tecwill Oy's plate granulation station are less than 1 mill. €, and the capacity of the station is 12 000 – 14 000 t/a (Väätäinen et al. 2000). If granulated ash is produced with full capacity (7.5 t/h) in one shift, totalling 10 000 t/a, the production costs may remain well below 20 €/t. With an annual production of 7 000 tons, the resulting production costs are a bit over 20 €/t. In practice, the daily production has been between 30 and 40 tons, so the production costs per ton have been higher.

The investment costs of drum granulating equipment, developed by Swedish Svedala Ab, are twice as high as those for the above mentioned plate granulating device. Drum granulating has been tested e.g. at UPM-Kymmene power plant at Kuusankoski during the summer 1996, but currently the method is not in use in Finland (Väätäinen et al. 2000). With this method the ash is moisturised and granulated in a drum with a diameter of two and length of 3 – 4 metres. The equipment includes so many belt conveyors, that the ash has time to harden enough.

Also ash rolling (pelletizing), i.e. use of pressing force, has been tested for ash granulation. A Finnish company LT Tuhkimo Oy is starting ash granulating with this method in Koria. The problem with rolling is the ash moisturising, but the moisture content of the final product may be even less than 5% (Väätäinen et al. 2000). As an example, in calculations for a smaller scale cylinder pressing device during experiments at Kannus research station of the Finnish Forest Research Institute, the investment costs were estimated to be 13 500 € and the productivity 1150 kg/h. With annual production of 2125 tons, the production costs of pelletized wood ash would be about 17 €/t.

In Finnish field studies (Hytönen & Takalo 1997), pelletized ash proved to be slowly diffusing. This refers also to slow dissolving of nutrients. However, the potassium content in ash pellets decreased notably during the study. Still, ash pellets seem to fulfil the biological targets. Pelletizing decreases the pH-shock effect both on soil and flora, which appears when great amounts of loose ash are used. Compared to loose ash, pelletizing may also decrease the impact on soil heavy metal contents after the ash spreading. Trees get nutrients during longer period and the risk of nutrient leaching to watercourses is minimised.

Pellets are also noticed to be very durable (Hytönen & Takalo 1997). If moist ash pellets are stored, pellet diffusing and thus also the share of fine particles seem to increase. This affects on spreading of pellets. On the other hand, changes in particle sizes of half-dried and dried ash pellets were insignificant.

4.1.3 Granulating with biosludge

Very large amounts of wood originated biosludge and ash are generated in Finnish pulp and paper industry. Both ash and biosludge contain nutrients necessary for forest growing. Pure ash is suitable especially for acidic, marshy forests. Ash and biosludge

together can be used especially for mineral soil forests, because of the nitrogen content of biosludge (Lindh et al. 2003). It is necessary to process biosludge and ash mixture to granules before spreading into forests, mainly because pure ash is too dustlike and it dissolves too fast. From granules the nutrients dissolve slowly enough for growing trees. Ash and biosludge should be granulated and transported into forests as simply, efficiently and economically as possible.

The aim of a Finnish project (Lindh et al. 2003) has been to develop a technically and economically feasible method for processing wood ash and biosludge of pulp and paper industry into forest fertiliser, and also to create a concept for taking the granules into forests. The main phases of the method are presented in Figure 2.

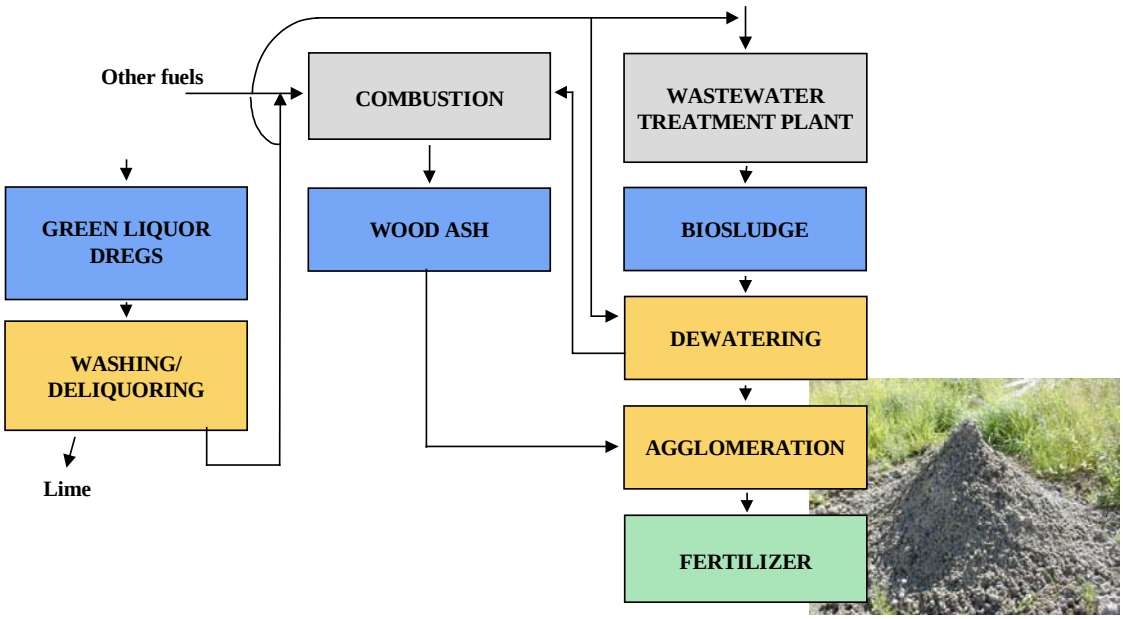

Figure 2. Wood ash granulating with biosludge.

The rotating method appeared to be the best of the granulating methods which were tested for different biosludge and ash mixtures. Granules were produced in both small and full-scale concrete mills. Ash quality, especially its cadmium content, appeared to impact on the granulation process (Lindh et al. 2003). Granules contained about two-thirds of biosludge and were covered by ash. Self-hardening of ash occurs when the water in the sludge reacts with the calcium in the ash. It is also possible to add extra nutrients into the granules.

The granules were found to bear moderate handling (Lindh et al. 2003). They can be stored in open air for a short period (weeks), but preferably in a covered place. Some characteristics of granules made in small-scale mill are presented in Table 20. Harmful dissolving of heavy metals was not found in laboratory-scale irrigation experiments. Heavy metals occur mainly in ash, while in bioludge the amount of heavy metals is very small. The large proportion of biosludge decreases the heavy metal content in granules.

Table 20. Some characteristics of ash-biosludge granules (Lindh et al. 2003).

Size of granules: proportion of 2 – 10 mm particles, %	85
Moisture content, %	50 – 60
Ash proportion (wet weight), %	33
Biosludge proportion (wet weight), %	67
Phosphorus content, g/kg	13 – 17
Nitrogen content, g/kg	15 – 17

In the created concept, the rotating granulation unit will operate at the pulp and paper mill site (Lindh et al. 2003). The granulation unit can be mounted on a truck, so that it is interchangeable with containers. The purpose is that after granulation the same truck can also transport the granules to forest in containers for spreading. The transportation of granules to forest can also be carried out using back hauls of fuel transport of the mill power plant.

The costs of granule production and spreading into forests are estimated to be 18.5 – 20 € per ton of granules, with a transport distance of 50 km (Lindh et al. 2003). The cost savings compared to landfilling are substantial, especially in the future, as the costs of landfilling are expected to increase significantly. The economical advantages are even greater, if also the assumed increase in tree growth is taken into account.

Especially birch saplings fertilised with ash-biosludge granules grew very well, at least as well as artificially fertilised saplings, in some cases even better (See Table 21). However, it could be useful to add some slowly dissolving extra nitrogen into the granules for long-term forest fertilising effect.

Table 21. Length of birch saplings (mm) after five months growing in greenhouse (Lindh et al. 2003).

Material and compounds	**Amount, biosludge + ash, t/ha**				**Average growth**
	0	**6 + 3 = 9**	**12 + 6 = 18**	**16 + 9 = 25**	
Biosl. + Ash 1	166	287	416	441	**328**
Biosl. + Ash 2	223	308	445	402	**344**
Biosl. + Ash 1 + N	171	358	371	406	**327**
Biosludge	146	319	373	328	**291**
Finnish saltpetre	171	359	429	402	**340**
Average growth	**175**	**326**	**407**	**396**	

The returning of nutrients of forest based biosludge and ash in the form of granules have proved to be one possibility to enhance the growing of wood biomass and the

production of bioenergy. The ash-biosludge granulation method is very practical and the economy of granule production and spreading into forests seems to be promising. Right timing and transport logistics is anyhow important. However, more research and development is still needed in pulp and paper mill conditions to test the concept with full-scale equipment. Sufficient amount of granules should be produced for studying the effects of ash-biosludge granules on forest growth and the dissolving behaviour of granules in practice (Lindh et al. 2003).

4.1.4 Classification

Wood ash utilisation as fertiliser is limited by high heavy metal contents, especially cadmium content. The cadmium contents in forest industry ashes vary between 3 – 30 mg/kg. The limit value for fertiliser use in agricultural crop fields is 3 mg/kg. One possibility to reduce heavy metal contents in ash is classification (Huotari et al. 1996).

The combustion conditions and fuel characteristics effect on the ash quantity and quality, which has impact on the utilisation options that can be used. In ash classification, it is essential to know, how heavy metals are enriched in ash particles of different sizes.

In the combustion zone, a great deal of heavy metals, e.g. Hg, Cd, Pb and Zn, is vaporised (Huotari et al. 1996). The level of heavy metal vaporisation is influenced by the steam pressure of the metal or its compound in the combustion temperatures used. Other impacting factors include heavy metal content in the ash components of the fuel, particle size distribution in the ash, and mixing. When cooling, the vaporised heavy metals sublimate on the un-vaporised ash particles in the flue gas. The arisen particles have a core of the original ash, from which the heavy metals have first vaporised and then formed a sublimated coating over the core. The ratio between the core and coating and their heavy metal contents determine the heavy metal content of the whole particle. For small particles, the surface area is large in relation with the mass, which causes high heavy metal contents. The determining factor in large particles is the core which contains less heavy metals.

The heavy metal concentration in coal ash has been studied. The results have shown that cadmium is enriched in small particles in varying manner, the coefficient being 2.2 – 5.7. If the enrichment in wood ash is at about the same level, it can be assumed that one-fourth of the smallest ash particles contain more than half of the total cadmium amount (Huotari et al. 1996). The cadmium content of the small particles would be almost 30 mg/kg while in other particles it would be about 6 mg/kg, provided that the cadmium content of ash is 12 mg/kg, the distribution is assumed to be 60% in small particles and 40% in larger ones, and the volume of large particles would be 75% of the total ash volume. In fine particles of wood fly ash, which is 2 – 17 weight-% of the total ash amount, 28 – 54 weight-% of the total cadmium content is concentrated.

The better the heavy metals vaporise in combustion, i.e. the higher the temperature, the better the heavy metals are classified in the last field of the electrostatic precipitator (Huotari et al. 1996). When this is the case, the heavy metals have been enriched in the

small particles, which have been carried along to the last field. The larger particles remain in earlier fields. On the other hand, the more the particles are loose from each other, the better they are classified in relation to the heavy metals: the small particles with high heavy metal contents do not remain in earlier fields with large particles, but drift to the last field.

In the following (Table 22), some technical options for ash classification in industrial scale are presented. The focus is more on those classifiers, which are able to efficiently classify particles with less than 10 µm diameter. Table 23 presents some laboratory scale classifiers.

Table 22. Industrial classifiers and separators (Huotari et al. 1996).

Classifier type	**Principle**	**Advantages**	**Disadvantages**
Gravity-based	The classifier is based on the different descending rate of different particle sizes in gravity field. Can mainly be used for rough pre-treatment	* favourable price * simple system * low operation costs	* low classifying efficiency and acuteness * high dead flow * cannot classify very small particles * suitable only for slow gas flows
Cyclones	Cyclones are based on centrifugal force, which causes particle classification.	* favourable price * easy to use * can classify 5 µm particles * small space requirement * low operation costs	* low classifying acuteness for small particles * high dead flow
Electrostatic precipitators	Electric field of voltage difference causes the particles to be charged. The charged particles drift to the electrodes of opposite charge.	* high classifying efficiency also for small particles * low pressure loss * equipment commonly used for flue gas cleaning * easy to use	* high price * no data on classifying acuteness * no data on dead flow
Cloth filters	Cloth filters are based on several phenomena, including screen effect, diffusion, electrostatic forces, gravity, fibre effect and inertia effect.	* excellent classifying efficiency even for small particles * easy to use * relatively inexpensive investment	* great pressure loss -> high operation costs * no data on particle distribution on cloth (probably low classifying acuteness) * no data on dead flow
Air classifiers	Air classifiers are based on different descending rate of particles in current of air. When leading the particle flow to rotating motion, centrifugal force makes classification more effective	* favourable price * low operation costs * simple structure * classified fine matter almost free from coarse substances	* high dead flow, even 40 – 60%
Wet scrubbers	The equipment is based on washing the particles out of air flow with mist	* favourable price * high classifying efficiency	* including water into the process * low classifying acuteness for small particles * high agglomeration because of humidity, so dead flow is significant

Table 23. Laboratory scale classifiers (Huotari et al. 1996).

Classifier type	**Principle**	**Advantages**	**Disadvantages**
Impactors	Impactors are based on particle classifying by different descending rates.	* favourable price * possibility to classify different size classes with one run by combining several impact washers one on the other	* bouncing of big particles on the impact washers, causing by-passing * dead flow over 10%
Laboratory scale cyclones	Cyclones are used also in laboratory scale (see Table 22).	* favourable price * easy to use	* high dead flow
Laboratory scale air classifiers	Air classifiers are used also in laboratory scale (see Table 22).		

VTT Energy has studied possibilities to classify ash into different particle size classes (Huotari et al. 1996). The aim was to decrease economically the heavy metal content of coarse matter and at the same time to keep the amount of fine matter at a low level. The purpose is to separate small particles (less than 10 µm) from bigger ones. This classifying aims at high acuteness and low dead flow.

Classification with this small particle size is difficult, and it is often necessary to compromise with the purity of the second fraction. The most important in this case is as good particle size classification as possible in the bigger sizes, i.e. there should not be small (less than 10 µm) particles in the coarse fraction. On the other hand, the aim is also to keep the amount of fine matter with concentrated heavy metals as small as possible. Because of these contradictory aims, it will probably be necessary to make compromises in particle classification into different size fractions.

Suitable equipment for classifying small particles could be cyclones, electrostatic precipitators, cloth filters and air classifiers. Of these, cyclones and air classifiers have quite high dead flows. There is not much information available in the literature concerning use of electrostatic precipitators or cloth filters in classification. However, suitability of electrostatic precipitators would be interesting, because they are already used for flue gas cleaning.

Gravity-based classifiers are suitable only for rough pre-treatment of the material, because of their poor classifying of fine particles. The disadvantage with wet scrubbers, on the other hand, is the poor classifying acuteness and the need to include water in the process, so their use in this context does not seem reasonable.

There are several possibilities to combine different equipment. For example, it is possible to use electrostatic precipitator for pre-classifying, and then use air classifier for post-treatment of coarse fractions. With this combination, it could be possible to reach good classification acuteness, and at the same time keep the share of fine matter in

the ash from the first field as small as possible. It is also possible to install cyclones and air classifiers in a series, and this way to decrease the dead flow. However, this option is expensive.

Use of electrostatic precipitator in ash classification

In the VTT Energy study (Huotari et al. 1996), ash samples were collected from different electrostatic precipitator fields at Finnish pulp and paper mills. The main fuel in these plants was bark (70 – 80%), except in UPM, where the main fuel during the sampling day was peat (52%). The cadmium contents of the ashes from different fields are presented in Table 24.

Table 24. Cadmium contents in ash samples of different fields, mg/kg (Huotari et al. 1996).

Mill	Field 1	Field 2	Field 3	Field 4
Kymi	2.4	6.5	9.8	
Enso 1	26.8	32.9	41.3	
Enso 2	18.7	26.2	32.2	
UPM	1.5	2.4	2.9	4.2
Enocell	9.2	33.4		

The particle size distribution in the samples proved, that the biggest particles remain in the first fields of the electrostatic precipitator, while the smaller ones drift to the last field. In every mill, the ash was well classified in fields especially for those heavy metals the content of which needs to be diminished in the main fraction. The contents of cadmium, zinc, copper, lead and arsenic were much lower in the first field than in the last one. For nickel and chromium no classification were found. Of nutrients, there were no differences between the fields in calcium contents, but potassium was enriched in the last field just like heavy metals. In these experiments, the results showed too high contents of cadmium, zinc and arsenic, so the ashes could not be used in field fertilising. The Finnish limit values for spreading on fields are presented in Table 26 in Chapter 5.

The study also tested possibilities to impact on the ash amounts and heavy metal contents in different fields by restricting and pulsing the current in the electrostatic precipitator. The aim was to ease the drifting of heavy metals to the last field and thus to decrease the heavy metal content of the first field even further.

The results showed that electrostatic precipitator can be used as an efficient classifier. The classifying was sometimes so efficient, than no separate classifier would be needed. If it is necessary to further impact on the ash heavy metal contents, it seems to be possible by adjusting the precipitator. However, the number of variables is too great, so it is difficult to estimate, what kind of adjustment would be needed for optimum results at any certain moment (Huotari et al. 1996).

At some mills, the ash quality from the first electrostatic precipitator field was adequate for utilisation, as the heavy metal contents were low enough. In these cases, only some additional conveyors would be needed. On the other hand, at some other mills for example a separator before the precipitator or a separate classifier would be needed to reach acceptable heavy metal contents for ash recycling.

4.2 SPREADING TECHNOLOGIES

Despite of the well-known good properties of ash, it has not been used for forest soil conditioning and fertilising in large scale (Väätäinen et al. 2000). The main reasons for this are the problems with spreading technologies. In drained peatlands the spreading can be carried out mainly in wintertime, when the ground is frozen.

In large-scale operations, ash is most often handled loose. It has been bagged only when delivering for research purposes on experimental plots (Korpilahti et al. 1998). When ash is pre-treated by self-hardening, it must be crushed for spreading. Crushing can be done with a crusher bucket equipped loader when loading for transport. If ash is granulated, it may be stored in a silo, from where the ash is dropped into the container of a lorry.

At forest site the lorry tips ash on ground from where it is taken with a grapple loader of a spreading tractor. When a helicopter does the spreading, ash is transported loose and loaded from the ground into spreading containers by a separate loader.

4.2.1 Spreading with tractor

When ash is spread from the ground by forwarder and tractor type devices, the stand must be thinned so that there are tracks for driving (Korpilahti et al. 1998). Best time for ash spreading is therefore just after logging. Ash recycling should be taken into consideration in planning of thinning of stands suitable for ash fertilisation.

In the ASH-project (Korpilahti et al. 1998), productivity studies of spreading were carried out, even though ash recycling was in the very start and the spreading devices were prototypes. The crawler forwarder reached the productivity of 6.3 m^3/h (7.2 t/h) when spreading granulated ash just after logging. The other forwarder-based machine reached 6.0 m^3/h (4.9 t/h) when spreading self-hardened ash in a stand which was thinned many years earlier. The lack of clear tracks and thick snow layer (65 cm) lowered the output clearly. Transportation distance from the storage to the spreading site was in both cases 500 metres.

Figure 3. Ash spreading with tractor (Swedish National Board of Forestry).

Spreading of granulated ash by a forwarder with a plate spreader has proved to be an efficient method (Väätäinen et al. 2000). Also the resulting evenness is better than when spreading loose ash. The evenness can be further improved by using blower spreading. The granulated ash is loaded in the container of the spreading device with the forwarder's crane, which has a bucket instead of a timber grab. For efficient work, the spreading device should be easy to assemble into a forwarder so that the machine could be flexibly used for both timber transport and ash spreading.

The storing of granulated ash in forest should be short, because longer storing weakens the quality of ash granules, and thus increases the spreading costs and decreases the nutrient contents (Väätäinen et al. 2000). Therefore, the long-distance transport of ash should be carried out only shortly before the spreading. This requires placing covered buffer storage at the mill, the capacity of which should be sufficient for possible volume growth in storage due to disturbances in spreading phase. When choosing spreading sites, also the existence of suitable forest storages should be taken into account. The smallest operational storage size is the size of a truck platform, about 20 tons, but the selection of storage number and locations should also be based on the transfer costs of the spreading devices.

There are also possibilities for smaller scale forest fertilising with granulated ash. The equipment and machines of private forest owners can be used to spread ash granules. Spreading can be carried out e.g. with an artificial fertiliser spreader mounted on a farm tractor, or with a forest spreader designed for spreading ash granules. If granulated ash were packed in large sacks, it would be possible to deliver smaller amounts for several individual users.

4.2.2 Spreading with helicopter

Refining ash into granulated form has improved the efficiency of ash spreading and thus provided possibilities for new spreading technologies, such as aerial spreading with a helicopter (Väätäinen et al. 2000). Currently spreading of granulated ash with a helicopter is used in larger scale in Northern Karelia, in Easttern Finland. The productivity of helicopter spreading is twice as high as with a forwarder or forest tractor, but it has proved to be several times more expensive. Unlike ground spreading with forwarder, aerial spreading is not fixed for any certain season or phase of forest management operations. Aerial ash spreading can be carried out year round, and also for un-thinned forests.

By using bigger helicopters with higher capacity, the spreading efficiency can be improved (Väätäinen et al. 2001). However, also the operation costs rise significantly, so the spreading costs per ton of ash are of the same level. Especially when the ash is to be spread with helicopter, it is important to place the forest storages as close to the spreading sites as possible. In most cases it is more economical to prepare a storage closer to the spreading site, if the other storage option would be one or two kilometres further away.

Ash spreading with helicopter can be improved by using modern GIS-systems. In the helicopter, GIS-based spreading management and control system controls the spreading and records e.g. flying routes and spread doses (Väätäinen et al. 2000). This improves the efficiency and reporting of spreading operations. Similar type of GIS-system can also be used in forwarder and forest tractor spreading.

4.2.3 Logistics costs of ash recycling

In a recent Finnish study (Väätäinen et al. 2000) the logistics chain of recycling granulated ash was simulated. The researchers also calculated the logistics costs for a couple of optional logistics chains for an existing Enocell Oy plant in Eastern Finland. Both investment and operation costs were taken into account. Some results are presented in Table 25. It must be noted, that as the costs are very case-specific, figures in the table should be considered only as a suggestive reference.

Table 25. Costs of optional ash recycling chains when the production of granulated ash is 6300 t/a. Investment costs per ton have been calculated using equal depreciation for 10 years with 6% interest rate and 20% residual value (Väätäinen et al. 2000).

Cost factor		**Options**					
		A*		**B***		**C***	
		Costs per ton, €/t					
1. Investment costs	**Investment, €**	Forest tractor spreading	Helicopter spreading	Forest tractor spreading	Helicopter spreading	Forest tractor spreading	Helicopter spreading
Remedy of barking chamber for ash storing	67 275			1.35			
New storage building + belt conveyor	269 100					5.20	
Total investment costs		**-**		**1.35**		**5.20**	
2. Operation costs of ash spreading chain							
Ash production (granulating)		27.25		27.25		27.25	
Short-distance transport		1.0		1.0			
Loading		0.35		0.35		0.35	
Long-distance transport (50 km)		3.85		3.85		3.85	
Forest tractor spreading (spreading distance 0.5 km)		8.05		8.05		8.05	
Helicopter spreading (spreading distance 1 km)			50.45		50.45		50.45
Total operation costs forest tractor – helicopter		**40.6 – 82.9**		**40.6 – 82.9**		**39.5 – 81.9**	
1 + 2: TOTAL COSTS		**40.6 – 82.9**		**41.9 – 84.3**		**44.7 – 87.1**	

* A. Current method; outdoors storing at the mill
B. Storing inside the old timber department, remedy of the building for ash storing (capacity 1000 m^3)
C. New storage building at the north side of the granulating plant. Transfer of granules from production to storage by a covered belt conveyor.

5 RELATED LEGISLATION

In the Fertiliser Act, the Finnish Ministry of Agriculture and Forestry has set limit values for heavy metal contents in soil conditioners and fertilisers (Table 26). These limit values do not apply, if wood or peat ash is spread to forest or used for landscaping. The cadmium content in wood ash from forest industry varies between 4 and 20 mg/kg. This is higher than the legislative limit value for agricultural use, so wood ash cannot be used for field fertilising.

Table 26. Limit values for heavy metal contents in ash used for field fertilising (Isännäinen & Huotari 1994).

Heavy metal	**Maximum content, mg/kg**
Mercury (Hg)	2
Cadmium (Cd)	3
Arsenic (As)	50
Nickel (Ni)	100
Lead (Pb)	150
Copper (Cu)	600
Zinc (Zn)	1500

In Finland and Sweden, there are no legislative limit values for heavy metals contents in ash, if the ash is spread to forests (Väätäinen et al. 2000). However, the harmfulness of heavy metals has been estimated (Nihlgård 1994, Isännäinen & Huotari 1994) and ecological limit values have been set for ashes in forest fertilising:

- Arsenic (As) is not as toxic as cadmium, but it has the same limit value, 10 ppm.
- Cadmium (Cd) is very toxic, and it should be discharged to the nature as little as possible.
- Chromium (Cr) is slightly toxic, but some researchers believe that it is needed in small amounts in forests. Chromium causes no problems, if the contents are 40 – 100 ppm.
- Copper (Cu) is lacking in some regions, especially in Southern Sweden. Applicable limit value for copper could be about 200 ppm, which is about the same amount as is taken away during forest harvesting.
- Mercury (Hg) is very toxic. It is discharged into the nature nearly always when hard coal or waste is combusted. Applicable limit value would be 0.1 – 0.3 ppm.
- Nickel (Ni) is a heavy metal, the content of which should not raise in the humus layer. Applicable limit value would be 100 ppm.

- Lead (Pb) contents in ash should not be more than 100 ppm, but the real values are often higher than that. The origin of lead in ash is not known. Either it is originally in the biofuel, or it is a pollutant, which remains in the ash during the combustion.
- Zinc (Zn) is needed in small amounts in forests, but as higher concentrations it is toxic. Especially fungi are sensitive to zinc. Many forests are in short of zinc. The applicable value for zinc would be about 10 g/kg.

Also other substances than heavy metals in soil disturb forest growth in too high concentrations. For example, contents of soluble aluminium have been noticed to increase to amounts which are harmful to plants and microfauna as a consequence of soil acidification (Isännäinen & Huotari 1994). In controlled field experiments soluble aluminium has weakened the growth of coniferous trees with concentrations of 10 – 50 mg/l in soil solution.

In Sweden Skogsstyrelsen (NBF, the National Board of Forestry) has prepared recommendations for heavy metal limit values in ash fertilisers, but they do not have legislative force.

The NBF's recommendations with respect to the chemical composition of ash products is summarised in Table 27. The maximum content of micro nutritive substances and heavy metals is set so that the maximum heavy metal input for spruce forests in Southern Sweden is not to be exceeded when the ash dosage is in the order of 3 t/ha (NBF 2001).

Table 27. Recommended minimum and maximum contents of substances in ash products intended for spreading in forest land (NBF 2001).

Substance	**Standard values**	
	Lowest	**Highest**
Macro nutritive substances, g/kg TS		
Calcium	125	
Magnesium	20	
Potassium	30	
Phosphorus	10	
Trace elements, mg/kg TS		
Boron		500
Copper		400
Zinc	1 000	7 000
Arsenic		30
Lead		300
Cadmium		30
Chromium		100
Mercury		3
Nickel		70
Vanadium		70
Other toxins injurious to the environment, mg/kg TS		
Total PAH		2*

* preliminary value

The values given in the table refer to primary contents of the ash product that is spread in the forest, i.e. after any addition of plant nutritive substances and bonding agents, but without water. If the ash product contains a lot of inert bed material or a bonding agent, the contents in the ash will be lower and can then be given per unit of weight of active substance. The chosen ash dosage should then be based on the active substance.

The main principle is that all substances are to fulfil the standard values (NBF 2001). Minor deviations for odd substances are, however, acceptable. If the minimum contents given fall short, then the possibility of introducing such nutritive substances to the ash product should be reconsidered.

If the introduction of ash entails a considerable increase in heavy metal content in forest land, then negative ecological effects may result in both the short and long term (NBF 2001). The risk of unwanted and acute effects in the ground is negligible if the ash has

been stabilised so that it will not dissolve for a long period of time. In order for unwanted long-term effects to be avoided, the input of heavy metals must be limited and the maximum values given in Tables 28 and 29 should not be exceeded (referring to the Swedish situation).

Table 28. Maximum input of heavy metals with ash or other compensatory fertilising agent into forest land with SPRUCE (or deciduous trees) during forest generation in Sweden (NBF 2001).

Heavy metal	**Southern Sweden***	**Central Sweden****	**Northern Sweden*****
	grams/hectare		
Arsenic	90	90	90
Cadmium	100	50	25
Chromium	300	200	150
Copper	1 200	600	500
Mercury	10	10	10
Nickel	200	200	200
Lead	1 000	500	250
Zinc	20 000	15 000	10 000
Vanadium	200	100	100

* = south of 60 degrees of latitude
** = between 60 and 64 degrees of latitude
*** = north of 64 degrees of latitude

Table 29. Maximum input of heavy metals with ash or other compensatory fertilising agent into forest land with PINE (or deciduous trees) during forest generation in Sweden (NBF 2001).

Heavy metal	**Southern Sweden***	**Central Sweden****	**Northern Sweden*****
	grams/hectare		
Arsenic	30	30	30
Cadmium	100	50	25
Chromium	300	200	200
Copper	800	800	500
Mercury	5	5	5
Nickel	200	200	200
Lead	400	200	100
Zinc	10 000	7 000	5 000
Vanadium	100	50	50

* = south of 60 degrees of latitude
** = between 60 and 64 degrees of latitude
*** = north of 64 degrees of latitude

The guiding principle is that the quantity of heavy metals reintroduced during one period of rotation is not to exceed the quantity taken out during that same period. A certain standardisation and practical adaptation has been carried out in compiling the values given. They are based on extraction in timber-rich stands and also with regards being taken to any local variation in content in biomass (NBF 2001). They are thus to be considered as maximum values that are, ordinarily, to be given a good margin.

The highest acceptable input of heavy metals with ash during forest generation is given in the tables above. The differences between spruce and pine depend partly on the biomass being lower in the pine stand than in the spruce stand and partly on the contents differing between the species of tree.

Only stabilised (chemically or physically) ash and ash that takes a long time to dissolve is to be used (NBF 2001). Stabilised ash is taken to be ash that is granulated, in pellet form or self-hardened/broken up ash. The target is that the ash products are to dissolve over a period of 5 to 25 years in the forest. Moreover, the initial speed of dissolution is to be so slow that no acute, unwanted effects occur after spreading.

6 HUMAN HEALTH AND SAFETY ASPECTS

Impurities in the air may cause health problems. When estimating the risks, the total amount of fine particles in the air, particle size distribution, their chemical composition and physical characteristics need to be taken into account (Juntunen 1982). Loose ash is very dusty, so the fine particles tend to fluff in the air during the handling and spreading. Moreover, the harmful compounds are typically enriched onto the smallest particles, which are the most likely to drift into lungs while inhaling. Therefore use of protective equipment is needed when working with ash. Self-hardening, granulating and other such treatments decrease the share of loose dust in ash, thus reducing the health risks.

One possible risk for human health could be concentrations of ash-based heavy metals in berries and mushrooms. However, Finnish studies (e.g. Moilanen 1998) have shown that heavy metals do not tend to accumulate in berries or mushrooms in harmful amounts. Only slight, statistically insignificant increases in concentrations were noticed, even in cases with relatively high cadmium contents in ash. Granulated or otherwise processed ash releases the heavy metals into the soil more slowly than untreated, loose ash, which decreases the health risks even further. In some cases, the heavy metal contents in berries and mushrooms have even been decreased with ash fertilising. One reason for this is presumably the liming effect of ash spreading (Moilanen & Korpilahti 2000).

Long-lasting exposure to cadmium (50 – 1000 µg Cd/m^3 air) could cause lung and renal injuries to human beings (Isännäinen & Huotari 1994). Exposure to cadmium together with lack of potassium and phosphorus could cause injuries in the skeletal system. Based on animal experiments it can be suspected, that cadmium is carcinogenic, causes placenta and testicle injuries and arterial hypertension. Injuries caused by arsenic appear in digestive system and peripheral nervous system. Long-lasting exposure to arsenic would cause skin changes, e.g. skin cancer. In addition, it would increase the risk for lung cancer. Certain chemical compounds of chromium and nickel are known to increase the risk of cancer. Chromate has been noticed to cause hypersensitivity reactions and allergic eczema, and as a result of long-lasting exposure also lung cancer. Zinc is not as harmful as Hg, Pb or Cr, but it might cause some general symptoms.

In spite of the severe injuries that may be caused by exposure to harmful ash compounds, wood ash fertilising can be considered quite safe, because the heavy metals do not tend to drift into berries and mushrooms. However, proper respiratory protective equipment needs to be used during ash handling and spreading to avoid inhaling harmful fine particles.

7 CONCLUSIONS

If the predicted strong increase in both use of timber raw material in industry and production of bioenergy will come true, also the amount of wood ash will increase significantly. The increased ash amounts could be recycled back to the forests which would ease the continuously growing waste problem. On the other hand, the nutrients which are removed during the harvesting operations could be returned to the forest to ensure constant productivity of the soil in long term.

The motivation behind wood ash fertilising is a bit different in Finland and Sweden. In Finland, the aim has traditionally been to increase the tree growth in peatland forests. In Sweden, on the other hand, the main target is to reduce the soil acidification in mineral soil forests. Both of these objectives can be reached with wood ash recycling. During the recent years, decreasing the burden in landfills has become more and more important in both countries. In the future, the anticipated increases in landfill fees will make ash recycling also economically feasible.

The ash characteristics and impacts on soil and trees have been studied for many years both in Finland and Sweden. The recent studies have tried to find new options for ash processing and spreading to improve the competitiveness of ash fertilising and to decrease the problems caused by dusting and harmful components of ash.

The aim of ash fertilisation is to compensate the nutrients removed with the harvested timber, balance nutrient status of the tree stand, counteract soil acidification and improve tree growth. Wood ash contains except for nitrogen all other elements, which are needed for tree growth and it presumably will not leach very easily (Korpilahti et al. 1998). Thus it can be considered to be an ecologically sound fertiliser. In several demonstrations wood ash recycling has proved to be a workable method. However, more experiences on long-term practises are still needed.

8 REFERENCES

Alakangas, E. 2000. Suomessa käytettävien polttoaineiden ominaisuuksia (Properties of fuels used in Finland). VTT Research Notes 2045, VTT Energy, Espoo 2000. (In Finnish)

Huotari, H., Isännäinen, S. & Hörkkä, S. 1996. Tuhkan raskasmetallipitoisuuksien pienentäminen luokittelemalla (Fraktionation as a means to decrease heavy metal contents in ash). VTT Energy, Research Report ENE23/T0003/96. Jyväskylä 1996. (In Finnish)

Hytönen, J. & Takalo, T. 1997. Tuhkapellettien kestävyys maastossa ja varastossa (Durability of ash pellets in terrain and storage). In: Nurmi, J., Hytönen, J. & Polet, K. (ed.): Energiapuusta puutuhkaksi (From energy wood to wood ash). Finnish Forest Research Institute, Reseach Notes 660. Kannus 1997. (In Finnish)

Isännäinen, S. & Huotari, H. 1994. Tuhkan ja metsäteollisuuden muiden jätejakeiden prosessointi lannoitekäyttöön soveltuvaksi (Processing of ash and other forest industry waste fractions for fertiliser use). VTT Energy, Jyväskylä 1994. (In Finnish)

Juntunen, M.-L. 1982. Tuhkan levityksen terveydellisten haittojen arviointi (Estimation of health risks in ash spreading). Finnish Forest Research Institute, Research Notes 62. Suonenjoki 1982. (In Finnish)

Korpilahti, A., Moilanen, M. & Finér, L. 1998. Biomass ash utilization in Finland. Joule III Programme / International Biomass Ash Workshop, Graz, Austria, October 1998.

Kuusela, S. 2003. Tuhkan rakeistamisen ja metsälevityksen käytäntöä (Ash granulation and forest spreading in practise). In: Presentations of Ash in growing of peatland forests seminar. 5.6.2003, Helsinki, Finland. (In Finnish)

Lindh, T., Isännäinen, S., Rantala, P.-R. & Kaunisto, S. 2003. Processing of wood ash and biosludge from pulp and paper industry for forest fertiliser. In: Proceedings of Bioenergy2003 International Nordic Bioenergy Conference. 2. – 5.9.2003, Jyväskylä, Finland.

Moilanen, M. 1998. Vaikutukset marjoihin, sieniin, mikrobistoon ja puuston kasvuun (Impacts on berries, mushrooms, micro-organisms and tree growth). In: Anttila, P. & Korpilahti, A. (ed.): Tuhkahankkeen väliseminaari 1998 – Esitelmien tiivistelmät (Intermediate seminar of ash project 1998 – abstracts of presentations). Metsäteho Reports 52, Helsinki 1998. (In Finnish)

Moilanen, M. & Korpilahti, A. 2000. Tuhkan käyttö suometsien lannoituksessa (Use of ash in fertilising peatland forests). TTS Institute, Forestry Bulletin 14/2000 (627). (In Finnish)

NBF 2001. Recommendations for the extraction of forest fuel and compensatory fertilising. Swedish National Board of Forestry, Meddelande (Research Notes) nr 2/2001.

Nihlgård, B. 1994. Kvalitetsvariation på askan – Önskemål om produktens ekologiska effekter (Quality variation in ash – Suggestion for product's ecological effects). BioMitt/Svebio-Konferens, Tema Askåterföring. (In Swedish)

Ring, E. 2002. Effects of fertilization with stabilized wood ash and N on soil-solution chemistry in a coniferous forest in Sweden. In: Ring, E., Jacobson, S. & Högbom, L., Massaindustrins barkaska åt skogen, Slutrapport (Recycling of ashes from the pulp industry, Final Report). Swedish Energy Agency, Project Reports TB-02/5.

SkogForsk 2000. Recycling of wood ash to forests. A guide for excursion-day for a visit of a Finnish group, 5-6 October 2000 to SkogForsk in Uppsala.

Taipale, R. 1996. Kiinteiden polttoaineiden ominaisuudet (Characteristics of solid fuels). M.Sc. thesis, University of Jyväskylä, Dept. of Chemistry, Laboratory of Applied chemistry. Jyväskylä 1996. (In Finnish)

Vesterinen, P. 2003. Regular recycling of wood ash to prevent waste production – RecAsh LIFE Environment demonstration project. State of the art seminar in Jyväskylä on 1.9.2003, Seminar report. Jyväskylä 2003.

Väätäinen, K., Sikanen, L. & Asikainen, A. 2000. Rakeistetun puutuhkan metsäänpalautuksen logistiikka (Logistics of recycling granulated wood ash back to forest). University of Joensuu, Faculty of Forestry, Research Notes 116. Joensuu 2000. (In Finnish)