Phytostabilization of mine tailings covered with fly ash and sewage sludge

Clara Neuschütz

Front cover: *Phalaris arundinacea* growing in sewage sludge on top of a fly ash sealing layer. Boliden, Sweden. Photo: Clara Neuschütz.

Abstract

Establishing plant communities is essential for the restoration of contaminated land. As potential cover materials, fly ash and sewage sludge can prevent formation of acid mine drainage from sulfidic mine waste. The aim of the thesis was to i) screen for plants that can be established in, and prevent leakage of metals and nutrients from sludge on top of ash and tailings, and ii) investigate root growth into sealing layers of ash and sludge. Analyses were performed under laboratory, greenhouse and field conditions using selected plant species to examine the release of Cd, Cu, Zn, N, and P from the materials. Plant physiological responses and interactions with fly ash were also investigated.

The data show that plants can decrease metal and nutrient leakage from the materials, and lower the elemental levels in the leachate, but with varying efficiencies among plant species. Plants capable of taking up both nitrate and ammonium were more efficient in preventing N leakage compared with those taking up primarily ammonium. Fast growing plants could raise the pH in acidic sludge leachate, but the initial pH decrease and N leakage was not counteracted by plants. Germination in fresh sludge was problematic, but enhanced by aeration of the sludge. In general, the accumulation of metals in plant shoots was low, especially if ash was located below the sludge. Fresh ash was phytotoxic (e.g., high alkalinity, salinity and metal levels) and induced the activity of stress-related enzymes in shoots. In sealing layers of aged and cured ash, roots could grow if the penetration resistance was low, or into the surface of stronger layers if the surface had become pulverized. The roots caused dissolution of calcium-rich minerals, possibly by exudation of saccharides. Addition of sludge to an ash layer increased root growth, likely due to decreased bulk density and pH, and nutrient addition. In conclusion, with selected plant species and a properly constructed cover, metal and nutrient leaching from the materials and root growth into the sealing layer can be restricted.

List of papers

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

I.   **Neuschütz, C. and Greger, M.** Ability of various plant species to prevent N, P, and metal leakage from sewage sludge. Accepted for publication by *International Journal of Phytoremediation.*

II.   **Neuschütz, C. and Greger, M.** Stabilization of mine tailings using fly ash and sewage sludge planted with *Phalaris arundinacea* L. Submitted to *Water, Air, and Soil Pollution.*

III.   **Neuschütz, C., Stoltz, E. and Greger, M.** 2006. Root penetration of sealing layers made of fly ash and sewage sludge. *Journal of Environmental Quality* 35:1260-1268.

IV.   **Neuschütz, C., Boström, D. and Greger, M.** Root growth into sealing layers of cured fly ash. Manuscript.

My contributions to the papers were as follows: I was responsible for the writing of all papers, with help from the co-authors. Together with my co-authors I planned all experiments, with the exception of one of the root penetration studies in Paper III. The field and laboratory work was performed by me, except application of material in the field and some elemental and mineral analysis, which are mentioned in the respective papers.

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Contents

1 Introduction

1.1 Phytostabilization

Generally the use of plants in the restoration of contaminated sites is termed phytoremediation, a technique that evolved during the last decades of the 20th century (Salt et al., 1995). When an area is only slightly contaminated, plants with a strong ability to take up metals from soils can be used in a process termed phytoextraction. However, when dealing with more heavily polluted sites, like sites for the disposal of mine tailings, plants that do not transport the metals to the shoots, but instead bind them in the root or the rhizosphere, are preferred. This approach is termed phytostabilization (Wong, 2003). The plants may also have beneficial effects on the treatment by causing physical stabilization, which prevents erosion, and by preventing rainwater from percolating down to underlying contaminated soil or mine tailings (Tordoff et al., 2000).

Introduction of plants directly on mine tailings has repeatedly been attempted, but has usually failed. This is due to the fact that such impoundments offer a harsh environment with high levels of heavy metals, low levels of macronutrients and poor substrate structure (Smith and Bradshaw, 1979; Clemensson-Lindell et al., 1992; Bell, 2001). Therefore, ameliorative materials like sewage sludge have been added in many cases, resulting in increased water holding capacity, reduced phytotoxicity and provision of nutrients over a long period of time (Hearing et al., 2000; Tordoff et al., 2000). The role of and function of plants in covers consisting of deep layers of fly ash and sewage sludge, however, remains to be examined.

1.2 Mine waste and acid mine drainage (AMD)

Extraction of metals by mining results in large volumes of wastes that have to be taken care of in order to avoid contamination of the environment. The problem arises primarily after extraction of non ferrous base metals like Cu, Pb and Zn, since these are found in ores with high sulfide content. After the metals have been extracted, approximately 95% of the rock is left as finely

grained sand called mine tailings, containing high levels of metal sulfides (Table 1), among which pyrite (FeS_2) is most abundant.

When mine waste containing pyrite comes into contact with oxygen and water, dissolved iron and sulfuric acid are produced through several complex reactions, of which one of the most important is the overall reaction (1) (Rimstidt and Vaughan, 2003):

$$FeS_2 + H_2O + 3.5\ O_2 \rightarrow Fe^{2+} + 2\ H^+ + 2\ SO_4^{2-} \tag{1}$$
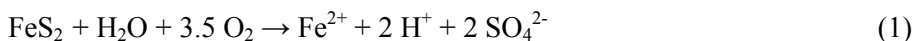
The Fe(II) ions formed may generate more acid through further oxidation, and turn into Fe(III), which may act as an oxidant on pyrite. The weathering process results in strongly acidic drainage water, commonly referred to as acid mine drainage (AMD), in which heavy metals can dissolve easily. Oxidation of other sulfides may also generate free metal ions as shown in reaction 2; however, this reaction does not generate any protons (Holmström, 2000):
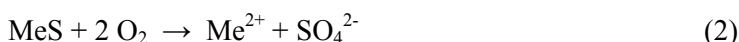
$$MeS + 2\ O_2 \rightarrow Me^{2+} + SO_4^{2-} \tag{2}$$

Table 1. Levels of elements in mine tailings, sewage sludge, fly ashes and common soil, and tolerable levels (of metals, As and B) for plants. Elements not analyzed are marked with "-".

Element ($g\ kg^{-1}$ DW)	Mine tailings[1]	Sewage sludge[2]	MSW fly ashes[3]	Biofuel fly ashes[4]	Background levels in soil[5]	Tolerable levels for plants[6]
Ca	-	28	74-130	230	14	
Fe	-	49	12-44	15	33	
K	-	4.4	22-62	90	27	
Mg	-	3.4	11-19	45	7.4	
Na	-	3.5	15-57	22	15	
P	-	27	4.8-9.6	10	1.1	
As	0.18	0.005	0.04-0.3	0.01	0.004	0.05
B	-	0.06		0.3	0.005	0.1
Cd	0.02	0.001	0.05-0.5	0.01	0.0002	0.005
Cu	1.0	0.4	0.6-3.2	0.1	0.02	0.1
Pb	0.5	0.03	5.3-26	0.2	0.02	0.1
S	144	9.0	11-45	11	0.4	
Zn	9.0	0.6	9-70	1.7	0.07	0.3

[1] Unoxidized mine tailings (73 samples) from Kristineberg, Sweden (Holmström et al., 2001)
[2] Average values from 48 Swedish sewage treatment plants in the year 2000 (Eriksson, 2001)
[3] Range of content in fly ash from incineration of municipal solid waste (MSW) (Wiles, 1996)
[4] Biofuel fly ashes from 12 Swedish power stations (Westermark and Gromulski, 1996)
[5] Topsoils (0-20 cm below soil surface) throughout Sweden (25 samples) (Eriksson, 2001)
[6] Proposed plant-tolerable levels of trace elements in soil (Pais and Jones, 2000)

Microorganisms present in the mine waste will affect the processes and increase or decrease the rate of metal mobilization (as reviewed by Ledin and Pedersen, 1996).

Each year approximately 20 million tons of reactive sulfidic mine tailings that must be disposed of are generated in Sweden (Fröberg and Höglund, 2004). About half of that amount can be used as filling mass in terminated mines, but the rest has to be stored in large impoundments (Södermark, 1986), for which natural lakes are often used (Fig. 1). If these mine tailings are left uncovered, the finely grained sand may be spread by the wind and contaminate the surrounding environment. Furthermore, the upper layer (0.5-1.5 m) will with time become oxidized, releasing sulfide-bound metals to surrounding waters (Holmström et al., 1999). In Sweden, where the bedrock has a low buffering capacity, the acidic drainage water from mine tailings may be a source of heavy metal leakage to various waters (Notter, 1993). Therefore, much effort has been invested in the development of techniques to limit these environmental problems.

Figure 1. Mine tailings impoundment without cover, at Lake Gillervattnet, Boliden. The total area of the lake is ~250 ha (Larsson et al., 2005) (Photo: Clara Neuschütz).

1.3 Dry cover treatment of mine tailings

One way to restrict the formation of AMD is to construct a dry cover that prevents weathering of the mine tailings either by acting as a barrier against oxygen and/or precipitating water, or as a consumer of oxygen (Elander et al., 1998). Beneficial is also if it increases the ground water table. A sufficient dry cover can be based on one material or a combination of different substrates. A multi-layer cover should consist of at least one compact sealing layer, and one more porous layer, which protects the sealing layer from erosion and temperature fluctuations and forms a suitable substrate for vegetation (Fig. 2). Traditionally, moraine has commonly been used to cover mine

tailings, but since the nutrient values are low and the extraction of moraine is expensive and detrimental to the landscape, new materials are under evaluation (Clemensson-Lindell et al., 1992). Waste materials from other industrial activities are attractive, since they are available at low cost. Two such products are sewage sludge from waste water treatment plants and fly ash from thermal power stations.

1.4 Sewage sludge

Sewage sludge is the solid material remaining from the treatment of waste water (Fytili and Zabaniotou, 2008). The treatment commonly includes a primary (chemical and physical treatment), secondary (biological treatment), and tertiary step (removal of nutrients). In Sweden each year, approximately 210 000 tons of sewage sludge are produced (Statistics Sweden, 2008). The composition is highly variable and levels of trace elements like Cd, Zn, Cu, and Pb (Table 1) may be high. Sewage sludge with low levels of pollutants is, however, considered to be a valuable plant fertilizer, due to its good water-holding capacity and high nutrient content (Tordoff et al., 2000). In restored industrial areas, like old mining sites, sewage sludge has frequently been used as an ameliorating cover material (Sopper, 1993; Hearing et al., 2000); in Sweden this application has garnered attention as agricultural use declines. Another term for sewage sludge is *"biosolids"*, which is often used for sludge low in pathogens, and which is considered suitable as soil amendment and fertilizer (WEF, 2009).

Apart from being a suitable substrate for plant establishment, sewage sludge may function well as a component of sealing layers (Mácsik et al., 2003), since the sludge in a compacted form can become almost impermeable to air and water (Scandiaconsult Sverige AB, 2001). However, sewage sludge alone does not have enough strength and durability to function as a sealing layer, and should therefore be used in combination with fly ash. Concerns that have been raised about the use of sewage sludge in dry covers are related to leakage of eutrophicating nutrients and toxic metals, emission of greenhouse gases (e.g., nitrous oxide and methane) and dispersal of pathogens. This thesis has focused on plant effects on nutrient and metal release.

1.5 Fly ash

Fly ash is produced during combustion of biofuel, coal, oil or municipal solid waste (MSW), and consists of particles that are captured from the smoke by filters (Wiles, 1996). Each year in Sweden, 435 000 tons of fly ash are produced and must be disposed of (Ribbing, 2007). The composition of

fly ash varies greatly depending on combusted material. Generally, fly ash contains high levels of Si, Ca, Al, S and a number of heavy metals (Table 1, Steenari et al., 1999). Properties that make fly ash suitable as a material in sealing layers include high alkalinity (Adriano et al., 1980), possibly representing a capacity to neutralize acidic drainage water, as well as the solidifying properties enabling ash to harden after being mixed with water (Steenari et al., 1999).

The hardening, or stabilizing, process is due to high levels of lime (CaO) and calcium sulfate ($CaSO_4$), which in contact with water form strong crystalline structures, in reactions similar to those that characterize the hardening of concrete (Steenari et al., 1999). The reactions include (from Steenari and Lindqvist, 1997):

- Carbonatization, e.g., $Ca(OH)_2$ (portlandite) + $CO_2 \rightarrow CaCO_3$ (calcite) + H_2O
- Formation of
  - Hydroxides, e.g., $CaO + H_2O \rightarrow Ca(OH)_2$
  - Gypsum, $CaSO_4 + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O$
  - Ettringite, e.g., $Ca_3Al_2O_6 + 3\ CaSO_4 \cdot 2H_2O + 26H_2O \rightarrow$
    $$Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26\ H_2O$$
  - Hydrated silicate and aluminum-silicate phases

The initial crystallization is rapid, whereas further stabilization reactions may continue for months, depending on the composition of the fly ash (Steenari et al., 1999). The strength of the hardened fly ashes seems to be correlated to water ratio (Xie and Xi, 2001) and to be favored by compaction of the material (Steenari et al., 1999) and high levels of calcium and available silica (Sivapullaiah et al., 1998).

Issues related to the use of fly ash in dry covers include its ability to harden and form a layer with low hydraulic permeability, as well as the risk of toxic leakage. Some ashes may alone form layers with low enough permeability (Tham and Andreas, 2008), while others need addition of other materials to decrease the permeability, e.g., sewage sludge (Mácsik et al., 2003), lime (Scheetz and Earle, 1998; Prashanth et al., 2001) or bentonite (Mollamahmutoglu and Yilmaz, 2001). In particular, municipal solid waste (MSW) ashes may contain high levels of Cd, Pb and Zn (Table 1). MSW ashes are considered to be hazardous waste in Sweden, making utilization in landfill covers controversial. However, in fly ash applied in the field weathering reactions may immobilize metals and prevent them from leaching (Wiles, 1996). Fly ash has even been used to decrease metal leaching from contaminated soils, by absorbing the metals on oxide and hydroxide surfaces as well as by increasing the pH (Stouraiti et al., 2002).

In Sweden, the possibilities of recycled ash have been studied in the context of the "Environmentally-friendly use of non-coal ashes" project, initiated in 2002 by the Swedish Thermal Engineering Research Institute (Vär-

meforsk). This has resulted in an increased use of ashes for landfills; construction of roads and parking places; forestry and mine tailing coverings. Approximately 50% of all ashes produced in Sweden were utilized in 2003; however, only a smaller fraction as cover material on mine tailings (Ribbing, 2007).

1.6 Ecophysiological aspects of plant establishment

For successful establishment of vegetation in a dry cover treatment, the plants must tolerate the conditions in the protective cover, but avoid growing into and penetrating the sealing layer (Fig. 2).
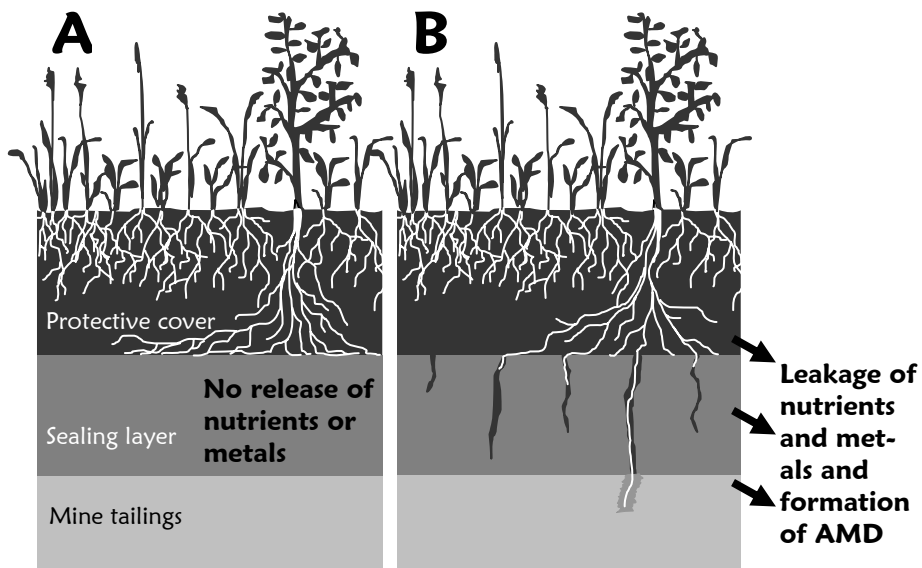

Figure 2. Possible roles of vegetation in a dry cover treatment of mine tailings, using sewage sludge and fly ash. The optimal situation is shown in picture A), where the plants prevent leakage of nutrients and metals, and do not grow into the sealing layer. In picture B) plants do not prevent nutrient and metal leakage from the sludge, but rather penetrate the sealing layer, leading to oxidation of the mine tailings and formation of acid mine drainage (AMD).

Since sewage sludge and fly ash do not fully resemble any natural soils, suitable plant species have to be selected after examination of their responses to the materials. Natural soils with a high content of moisture and organic matter (such as bogs) resemble sewage sludge in some aspects. However, since they are usually formed in cold climates with slow nutrient turnover (Brady

and Weil, 2002), plants growing in these soils are adapted to low nutrient levels and would not be optimal for establishment in sewage sludge. The underlying fly ash layer may in some ways resemble soils formed by deposition of volcanic ash (Andisols), with crystalline structures and high pH (Brady and Weil, 2002). These soils have, however, been exposed to soil-forming processes for several thousands of years, and are much less reactive than newly applied fly ash. Hypothetically, plants that would avoid growing into an ash sealing layer are those sensitive toward alkaline and calcium-rich soils (so called calcifuges). Nevertheless, these plants are generally adapted to soils with low salinity and nutrient content (Larcher, 2003), and may not tolerate the conditions in sewage sludge. Appropriate plants would, instead, be those with a high nutrient uptake and a weak ability to grow into compacted soil.

An ability to utilize nitrogen both in the form of ammonium (NH_4) and nitrate (NO_3) should be beneficial, since both forms will occur in sewage sludge after application to land. Most plant species have an optimal growth with a mixture of ammonium and nitrate (Marschner 1995), however, the preferences may vary between plants adapted to different climates and soil conditions. Plants adapted to cold climates, where the nutrient turnover rate is slow and soils often have a low pH, generally have a higher ability to take up ammonium than nitrate, and plants growing in Ca-rich and more alkaline environments have a higher preference for nitrate (Gigon and Rorison 1972). Furthermore, plants occurring early in the succession (such as many ruderate species) often have a greater ability to adapt to variations in nitrogen species (Min et al. 2000), while woody plants occurring late in the succession usually are dependent on organically bound nitrogen and ammonium (Nordin et al. 2001).

In re-vegetation of mine waste covered with sewage sludge, it has been common to introduce various grass species with tolerance toward metals and salinity (Bendfeldt et al., 2001; Evanylo et al., 2005; Santibáñez et al., 2008). It may be assumed that grasses have shallower root systems than woody plants. However, rooting depth has been more strongly related to climatic variables than to vegetation types (Schenk and Jackson, 2002). Therefore, further studies on physiological traits rendering plants suitable for growth in sewage sludge and fly ash should be performed, to optimize the use of plants in the restoration of mining sites.

2 Aim

The aim was to increase our knowledge of the interaction between plants and the waste product sewage sludge and fly ash used in treatment of sulfidic mine tailings. I examined physiological responses of plants growing in the materials and mechanisms behind plant-induced impacts on the materials. The goal was, further, to improve our understanding of the extent to which plants can be used in phytostabilization of mine waste, and how sewage sludge and fly ashes can be used in an environmentally safe way.

The project was divided in two parts:

1. *The establishment of plants in sewage sludge and their effect on leakage of nutrients and metals. The specific aim was to reveal:*
   a. plant species that are capable of establishment in sewage sludge in a temperate climate
   b. the effect of various plant species on leakage of nutrients and metals from sewage sludge, fly ash, and mine tailings, and the mechanisms involved
   c. the extent to which plants growing in a cover of sewage sludge and fly ash accumulate metals in their shoots, posing a hazard to grazing animals

2. *Root penetration of sealing layers containing fly ash. The specific aim was to determine:*
   a. how plants respond physiologically toward fly ashes with various properties
   b. the properties and mechanical resistance necessary in an ash sealing layer to prevent penetration of plant roots
   c. whether plants can affect the strength of a sealing layer of fly ash, for instance by exudation of root substances

Experiments were performed within a time frame of days to several months; root growth was observed in the field for up to eight years. The results are presented in the four papers attached. Included in the thesis are also data from preliminary studies concerning plant establishment in sewage sludge, uptake and distribution of metals in plants, and concentrations of N and P in sewage sludge pore water.

3 Comments on materials and methods
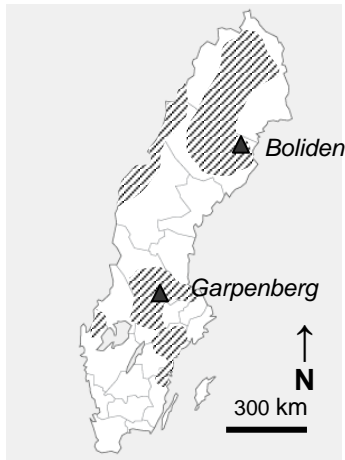
3.1 Field sites

Figure 3. Field work has been performed at Boliden and Garpenberg (Paper IV). Marked areas are regions in Sweden with sulfidic bedrock.

The field experiments (Paper IV) were performed at the mine tailings impoundments at Gillervattnet, Boliden (64°52'N, 20°22'E) (Fig. 3). Observations were also performed at Garpenberg (60°19'N, 16°09'E), in test plots for a project initiated by the municipality of Hedemora together with Boliden AB and Högskolan Dalarna. Various cover treatments have been constructed at both these sites, using waste products from wastewater treatment plants, thermal power stations and the wood industry, in order to evaluate the possibilities of utilizing these materials.

At the tailings impoundment in Boliden, sealing layers consisting of either 100% biofuel fly ash (from Munksund and Hedensbyn), 70% fly ash and 30% sewage sludge (based on volume), or 100% sewage sludge were constructed, with depths of 0.5 to 1.0 m. Sludge has been applied at depths of 0.25 to 0.5 m on top of these sealing layers (Fig. 4). The test plots have been built gradually and vegetation introduced during the years 2003 to 2006. These plots have been used for investigations of plant establishment, uptake of metals in shoots, pore water chemistry in the sewage sludge, and root penetration of sealing layers.

At the tailings impoundment at Västra sandmagasinet, Garpenberg, test plots were constructed in 1998, with waste products from the local paper board industry (Stora Enso Fors). A 30 cm deep layer of fly ash was applied, covered with a 45 cm thick layer of paper pulp sludge mixed with mine tailings. Introduction of various tree species was performed in 1999 and 2000, whereas the root growth was studied in autumn 2007.

Figure 4. Vegetated test plots in sewage sludge on top of a sealing layer of fly ash at the mine tailings impoundments in Boliden. (Photo: Clara Neuschütz).

3.2 Plant species used

Plant species suitable for establishment in dry covers of sewage sludge and fly ash on mine tailings, should be tolerant to the materials and able to prevent leakage of nutrients and metals without accumulating metals in their shoots. Moreover, the plant roots should have a weak ability to penetrate compacted fly ash layers. The plants also need to tolerate a colder climate, since most mining areas in Sweden are situated in the north or middle part of the country (Fig. 3). The mean temperature of Västerbotten province, where Boliden is situated, ranges from -6°C to -15°C in January and from 12 to 15°C in July; annual precipitation is 500 to 700 mm (Vedin, 2007). The Dalarna province, where Garpenberg is located, has a mean temperature in January of -5.5°C to -12°C and in July of 10°C to 16°C, and an annual precipitation of 600 to 1000 mm (Vedin, 2005). Different types of plants, such as herbs, trees and grasses with varying anatomical and physiological capacities were included in the analyses (Table 2, Fig. 5). Certain plants are of particular interest since they may establish through natural succession, while others can easily be manually dispersed by seeds. In addition, crops that can be used for biofuel may be of future interest and were included in the project. To find plant species that are adapted to the conditions in these areas, an inventory of naturally dispersed plant species was performed at a sewage sludge disposal site next to the mine tailings in Boliden, as well as at a site next to the mine tailings in Garpenberg, where a thin layer of untreated sewage sludge has continued to spread over 30 years. Out of more than 70 plant species found growing naturally in both areas, a smaller number were chosen for later studies (Table 2, Fig. 5).

Table 2. Plant species used in the experiments presented in the thesis. Their life-history, life-form, and minimum rooting depth are given (USDA, NRCS 2009).

Latin name	Common name	Life-history and life-form	Min. root depth (cm)
Agrostis capillaris L.*	Common bent	Perennial grass	30
Betula pendula Roth.*	Silver birch	Perennial deciduous tree	60
Cannabis sativa L.	Industrial hemp	Annual herb	
Epilobium angustifolium L.*	Fireweed	Perennial herb	25
Phalaris arundinacea L.	Reed canary grass	Perennial grass	35
Phaseolus vulgaris L.	Dwarf bean	Annual herb	
Picea abies (L.) H. Karst.*	Norway spruce	Perennial coniferous tree	70
Pinus sylvestris L.*	Scots pine	Perennial coniferous tree	50
Pisum sativum L.	Garden pea	Annual herb	
Poa pratensis L.*	Kentucky blue-grass	Perennial grass	25
Salix myrsinifolia Salisb.*	Dark-leaved willow	Perennial deciduous shrub	
Salix viminalis L.	Basket willow	Perennial deciduous tree	
Tussilago farfara L.*	Coldsfoot	Perennial herb	

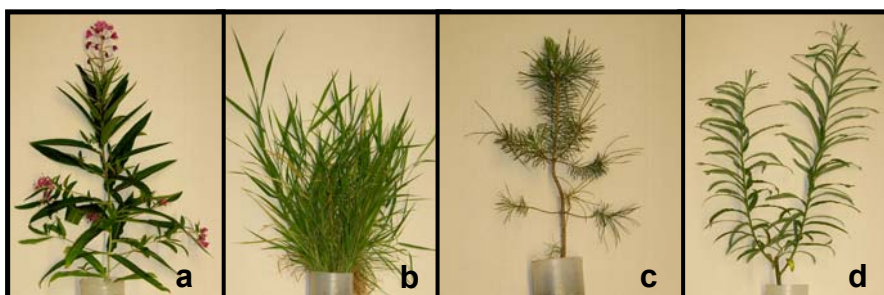**Plant species found growing naturally at the mining sites*

Figure 5. Plant species used for the leakage studies (Papers I and II): a) *Epilobium angustifolium,* b) *Phalaris arundinacea,* c) *Pinus sylvestris,* and d) *Salix viminalis.* (Photo: Clara Neuschütz).

Phalaris arundinacea, Salix viminalis, and *Cannabis sativa* were selected to represent energy crops in Sweden (Venendaal et al., 1997). Cultivation could be of economic interest, and these plant species are known to have a high nutrient uptake. However, *S. viminalis* has a relatively low tolerance toward frost (Tahvanainen and Rytkönen, 1999), and may therefore be difficult to cultivate in the northernmost parts of Sweden.

In the toxicity test of fly ash extracts in Paper III, *Pisum sativum* was used, although this is not a plant intended for establishment at treated mining areas. Advantages of using this plant in short-term toxicity tests are the fast growth rate of primary roots and the nutrient-rich seed, making addition of

nutrients to the solution unnecessary. A toxicity test performed in the same way but with 19-day-old *P. sylvestris* seedlings in dilution series of two of the fly ashes showed that these plants were more sensitive toward the ashes than *P. sativum*. Similarly, in the study of physiological stress response toward diluted fly ash extracts (Paper III), *Phaseolus vulgaris* was used because it has previously been used in standardized biological test systems (Van Assche and Clijsters, 1990).

When comparing different plant species, one has to consider variations in growth pattern and life-history. An annual herb may, for instance, increase its biomass faster during the first growing season than a perennial tree, while the tree will have higher biomass within a couple of years. In many cases, plants of the same age can be used; if the biomass differs, this can be accounted for as a species difference. However, when roots are for instance washed for the collection of root exudates, a large variation in root biomass can be problematic if the same amount of washing liquid is used. The diffusion of elements from the roots could in that case be affected. To avoid such errors, I have in some experiments used plants with similar biomass. This has been performed either by varying the time of pre-cultivation, or by varying the number of plants in each container. In the field study, seeds, cuttings and one to several-year-old plantlets were used to study the ability to establish and grow into the sealing layer.

3.3 Waste products

Fly ashes were received from seven different thermal power stations using varying combustion techniques and types of fuel (Table 3). In a circulating fluidized bed (CFB) furnace, finely grained sand is used as bed material to homogenize the heat distribution, thus reducing the temperature requirements (800°C instead of conventional 1450°C) (Scheetz and Earle, 1998). The amount of Si in ashes from CFB combustors is usually higher than from traditional grating furnaces, due to residual bed material particles. This can have an impact on hardening capacity, since higher puzzolanic ability has been related to higher levels of available Si (Sivapullaiah et al., 1998).

The sewage sludge that was used in greenhouse and field studies originated from the Henriksdal sewage treatment plant, Stockholm Vatten, Stockholm, which treats a large fraction of all sewage produced by households in Stockholm. Iron sulfate is used as a precipitation agent at this treatment plant; the sludge is stabilized unaerobically and dewatered to a dry matter content of about 30%.

Table 3. *Origin and type of fuel and furnace of the fly ashes used in the thesis.*

Origin	Fuel	Furnace	Paper
Hedensbyn, Skellefteå Kraft	80% biofuel, 20% peat	CFB[1]	III, IV
Hässelby	Biofuel	Pulverized fuel	III
Högdalen	Wood construction waste	CFB[1]	III
Iggesund Paperboard	Bark	Grate-fired boiler	IV
Munksund, SCA Packaging	91% biofuel, 6% recycled paper, 3% oil	CFB[1]	II, III, IV
Stora Enso Fors Mill	Biofuel	CFB[1]	II, IV
Umeå Energi	Municipal solid waste	Grate-fired boiler	III, IV

[1]CFB = Circulating Fluidized Bed

3.4 Analysis of nutrients and metals

The analysis of nutrients in leachates (Papers I and II) was performed spectrophotometrically, at 640 nm for NH_4-N, 220 nm for NO_3-N (Clesceri and Greenberg, 1995), and at 880 nm for PO_4-P (Murphy and Riley, 1962). Before analysis the samples were filtered ($<0.45\mu m$), resulting in a determination of dissolved species but not total content. Interference due to organic matter can be a problem during spectrophotometric analysis of nitrate. The high nitrate concentrations, however, made dilution possible, so that the problem was avoided.

The reason for analyzing the metals Cd, Cu, and Zn in leachate (Papers I and II) was their high abundance in waste materials (Table 1) and their toxicity to water organisms (Fjällborg et al., 2005; Madoni and Romeo, 2006), which may affect organisms downstream from the restored mining site. Analysis was performed using an atomic absorption spectrophotometer (AAS, Varian SpectraAA-100, Springvale, Australia), with flame technique for Zn and furnace (GTA-97) for Cd and Cu. Three standards were added to each sample to correct for interaction of the sample matrix. Upon analysis of plant metal content, we included certified reference material (CRM) from *P. arundinacea* (NJV 94-4) and *Salix* (NJV 94-3), originating from the Swedish University of Agricultural Sciences, Uppsala, Sweden, in order to validate the digestion procedure and to ensure high-quality metal analysis.

The amount of metals in the sewage sludge (Paper II) was analyzed after digestion in 7M HNO_3 (for 30 minutes at 120°C) (according to Swedish Standard SS 028150). This method does not dissolve the metal fraction bound to silicate minerals, however, extracting close to the total amount of metals from rich organic substrates (Sastre et al., 2002).

3.5 Determination of penetration resistance

The resistance that a root is encountering in a soil can be measured using a penetrometer. This device records either the pressure required to press a steel probe (usually with a tip semiangle of 15° or 30°) to a certain depth or at a certain rate, or the depth of penetration under a constant load (Bennie, 1991). The result will not completely capture the resistance that the root is exposed to, since no apparatus can imitate all features of a root, such as exudation of lubricating mucilage and radial growth of cells. The penetrometer used in Papers II and III was constructed at the Department of Soil Science, Swedish University of Agricultural Sciences, Uppsala. The cone had a semiangle of 15°, a diameter of 4.1 mm, and was mounted on a 3 mm wide and 30 mm long piston on an apparatus originally constructed for measurement of soil aggregate strength (Fig. 6).
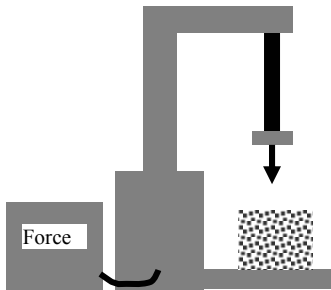

Figure 6. Schematic picture of the penetrometer used for determining penetration resistance in cured fly ash (Paper II, IV).

By determining the maximal force that was needed to drive the cone 10 mm down into the material, the penetration resistance was calculated. One problem with using a laboratory penetrometer is that only smaller samples can be measured. Smaller aggregates will crack earlier than larger aggregates (Misra et al., 1986), causing a lower resistance than would be the case in a homogenous layer in the field. Therefore, the penetration resistance of fly ash from the field (Paper IV) may be underestimated. In the greenhouse study, however, the penetration resistance was measured in fly ash layers in planting pots maintained under the same conditions as those experienced by roots encountering the fly ash. For the experiments in Paper III, we used the bulk density of the fly ash samples as a measure of mechanical impedance, since the penetrometer had not been constructed at that time. The penetration resistance depends partly on the bulk density (Bennie, 1991; Vaz et al., 2001), which has been used as a measure of soil strength in several studies of plant responses to soil compaction (Nasr and Selles, 1995; Stirzaker et al., 1996; Arvidsson, 1999). Other important factors are water content of the soil and porosity (Bennie, 1991), which was not analyzed in the study in Paper III, but was investigated in Paper IV. The occurrence of biopores has been found to greatly enhance the possibilities of root growth in soils with high bulk density (Stirzaker et al., 1996).

4 Results and Discussion

4.1 Plant growth in sewage sludge and effect on the leachate

4.1.1 Establishment of plants in sewage sludge

The high levels of nutrients in sewage sludge make it a suitable substrate for plants. However, even though it contains all essential plant nutrients, the proportions are not ideal for most plants. Often a surplus of P and/or a deficiency of K is the issue (Bramryd, 2002). Moreover, the establishment of plants in sewage sludge can be a problem due to high salinity (Abad et al., 2001), high levels of metals, and ammonium (Fjällborg and Dave, 2003). This can be ameliorated if the sludge is mixed with soil or peat (Garcia-Gomez et al., 2002). A decrease in pH, due to reactions such as nitrification, decomposition of organic S, or oxidation of Fe sulfides (Merrington et al., 2003), may cause an increase in availability of toxic metals, but can be avoided by addition of a liming substrate (Sajwan et al., 2003).

Germination and the establishment of seeds or seedlings in fresh sewage sludge was often problematic, both in greenhouse (Paper I, II) and field experiments (Paper IV). A hard sludge surface caused by dry weather could further obstruct germination. A germination test (unpublished) showed that germination and growth during the first three weeks in sewage sludge was considerably lower than in planting soil (Fig. 6). The plant species used were: *Agrostis capillaris. Betula pendula, Epilobium angustifolium, Phalaris arundinacea, Poa pratensis,* and *Pinus sylvestri*s. Even cuttings of *Salix myrsinifolia* that were transferred to pots with pure sewage sludge had difficulties in establishing as compared to those transferred to planting soil (Fig. 7). However, once the plants have passed this stage and survived the first months they display robust growth in the sludge.

To ensure successful establishment of plants in the greenhouse experiments, the sludge needed to be dispersed and exposed to air for a couple of weeks. The plants were also in some cases pre-cultivated in planting soil until roots had developed (Paper II). Thereafter they were transferred to

sewage sludge. In field experiments, we observed that a layer of bark between the sealing layer of fly ash and the protective sludge cover increased the rate of survival one month after transferral of plantlets (of *Betula pubescens, Picea abies* and *Pinus sylvestris*), compared to plantlets established in only sludge. On average, 74% of all plants survived when bark was added compared with 19% in only sludge (unpublished data). Germination of *P. arundinacea* was also more efficient when bark was present, while no effect was seen in *S. myrsinifolia* and *S. caprea*. It is possible that the bark improved the conditions by increasing the oxygen levels in the otherwise compacted sludge, as well as protecting against toxic effects from the fly ash below. With time composting and degradation processes will occur in the sludge, making it more tolerable for plant germination (Fuentes et al., 2006), for instance by decreasing the ammonium levels by nitrification (Smith and Tibbett, 2004).
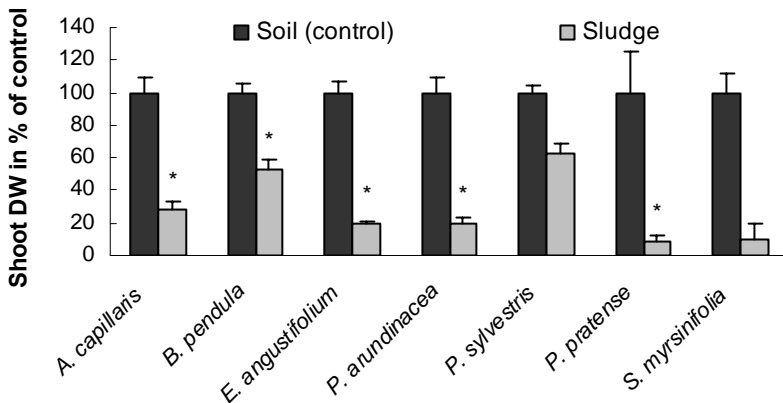

Figure 7. Shoot biomass (dry weight in % of control) of various plant species three weeks after seeding in planting soil (control) or sewage sludge. *Salix myrsinifolia* was introduced as cuttings and harvested after 4 weeks (n=5, +SE) (unpublished data). Significant differences ($p<0.05$) between sludge treatment and control are marked with a star.

Thus, to rapidly establish plants in fresh sewage sludge, the sludge should be aerated, or a material such as bark can be added. As a dry sludge surface should be avoided, application and establishment of plants should preferably be performed during spring or autumn.

4.1.2 Metal uptake in plants

From other studies, the plant uptake of metals from sewage sludge has been found moderate and not exceeding levels that are toxic for plants (Miller et al., 1995; Pichtel and Anderson, 1997; Evanylo et al., 2005) or animals (Stuczynski et al., 2007). However, addition of a liming material has been

recommended (Brown et al., 2003; Sajwan et al., 2003) to prevent pH decrease in the sludge that otherwise can increase metal phytoavailability (Antoniadis et al., 2008).

In this thesis, analysis of metal uptake was performed in plants that had been growing for 2.5 months in sewage sludge alone, or on top of fly ash and mine tailings (Papers I and II) (Table 4). Furthermore, metal content was determined in shoots of five different plant species collected in the field after growth in sludge on top of a fly ash sealing layer for up to 3 years. The shoot concentrations of Cd were low in all cases. Concerning Cu and Zn, the concentrations reached the maximum tolerable levels for animal feed (NRC, 2005) in some of the plants (Table 4). These levels are, however, recommendations for domestic animals ingesting no other food (NRC, 2005). Higher levels should be tolerable for wild animals that can move freely and graze over large areas.

Table 4. Average levels of Cd, Cu, and Zn in shoot tissue of various plant species used in the field (unpublished) and greenhouse experiments (Papers I and II). The recommended maximum tolerable levels in feed for domestic animals (mg kg^{-1} air dried forage) (NRC, 2005) are also presented.

Plant species	Field (F) or greenhouse (G) study	Cd	Cu	Zn
Cannabis sativa	F		24	111
Epilobium angustifolium	G	0.2-0.4	7-18	94-190
Phalaris arundinacea	F+G	0.1-0.2	11-20	135-342
Poa annua	F		17	115
Pinus sylvestris	G	0.04-0.1	6-8	36-78
Salix myrsinifolia	F		13	1090
Salix viminalis	F+G	0.3-0.4	11-22	140-290
Tolerable levels for animals		10	15-500	300-1000

Similarly high shoot Zn levels have been found in *Salix* species growing in mine tailings at Boliden, explained by the high capacity of the plants to translocate metals to the shoots (Stoltz and Greger, 2002). In one of the greenhouse experiments the uptake of Cd, Cu and Zn was analyzed in *P. arundinacea* (Paper II). If looking at the distribution of Cd, Cu and Zn among roots, shoots, and sludge after harvest, it turned out that various metals were distributed differently (Fig. 8) (unpublished data). While shoot uptake of Cd and Cu was restricted, transport of Zn to the shoots was higher. This study also showed that growth in sewage sludge did not significantly increase metal uptake as compared with growth in planting soil (containing 80% peat and 20% clay). Furthermore, the plants were not able to change the

metal concentrations in the sludge during the experiment, and the accumulation factor (metal concentration in the plant tissue divided by metal concentration in the sludge) was below 1 in all cases. This means that the plants did not accumulate a higher concentration of metals in their tissue than was found in the surrounding substrate (not shown). The highest accumulation factors were observed for Zn (0.52 in shoots, and 0.77 in roots). Plants used in phytostabilization should preferably exhibit weak accumulation of metals in shoots, to avoid transferring toxic metals into the food chain.
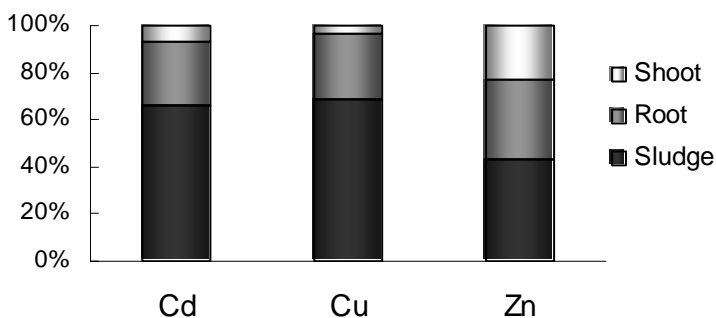

Figure 8. Distribution of metals in sewage sludge, roots and shoots of *P. arundinacea* after 11 weeks of growth (n=7) (unpublished data).

In the field, we found that Cu and Zn concentrations in shoots of *P. arundinacea* that had been growing in sludge for 0.5 to 3 years did not vary significantly among the years (not shown). Thus, either the plants maintained a constant level of uptake, or the availability of these metals stayed constant over the years.

The presence of fly ash below the sewage sludge prevented Cu and Zn uptake in roots of *P. arundinacea*, and in shoots when mine tailings were also included (Paper II). It is likely that the alkalinity of the fly ash decreased the availability of metals, since many metals are less soluble at higher pH (in the region close to neutral) (Villar and Garcia, 2002; Basta et al., 2005). Furthermore, fly ashes contribute Mn and Fe oxides, minerals that have been suggested to be responsible for decreased uptake of metals in plants grown in fly ash-stabilized sewage sludge (Su and Wong, 2003).

The presence of mine tailings below the sludge had a minor effect on metal uptake in plants (Paper II). Only Cu was somewhat higher in shoots when the tailings were present. Other studies have evaluated the effect on metal uptake of adding sewage sludge to mine tailings, with varying results. In some cases, metal uptake in plants has decreased when sludge is added (Theodoratos et al., 2000; Ye et al., 2001), as compared to the absence of organic amendment; in other cases, uptake has increased (Rate et al., 2004; Santibáñez et al., 2008). The result has also been found to vary depending on the weathering status of the tailings, with a preventive effect of sludge on

plant metal uptake from oxidized tailings, but an increasing effect on uptake from non-oxidized tailings (Stjernman Forsberg, 2008).

In conclusion, the introduction of plants in a protective cover of sewage sludge on top of fly ash does not expose grazing animals to toxic levels of Cd, Cu or Zn, provided that certain metal-accumulating plant species are avoided.

4.1.3 Leakage of nutrients

Application of sewage sludge at mine disposal sites poses a risk of nutrient leakage to the surroundings, especially of nitrogen; phosphorus has been found firmly bound in the sludge (Paper I, Stehouwer et al., 2006). Plant establishment can decrease leakage (Santibáñez et al., 2007). However, since the availability of nutrients from the sludge does not necessarily match the nutrient needs of the plants (Bramryd, 2002), superfluous elements can be subjected to leaching.

Data obtained from the greenhouse experiments demonstrate that plant uptake of water is one of the most important factors in leakage prevention, since it will decrease the total amount of leachate formed (Papers I and II). Water uptake can also cause aeration of the sludge, rendering phosphorus more firmly bound to FeOOH (Gomez et al., 1999). In the leakage study presented in Paper I, the total leakage of phosphate (Fig. 9) and nitrate, but not ammonium, correlated negatively with the water uptake of plants.
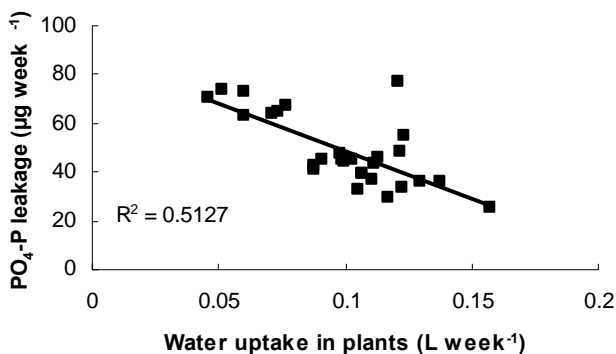

Figure 9. Total leakage of phosphate-P in relation to water uptake per week of four plant species growing in containers with sludge for 10 weeks. (Paper I).

Hydrological conditions affected by plants are, thus, of great importance for the stabilizing effect, and are schematically shown in Fig. 10. Fast-growing plants with a high transpiration rate should theoretically be the most favorable plants; however, it was found that the solution is not that simple (Paper I). Both *Phalaris arundinacea* and *Salix viminalis* are fast-growing energy crops, with high water uptake and biomass production (Venendaal et al., 1997). The concentrations of nutrients in the leachate varied, however, among the species, with *S. viminalis* causing higher concentrations of nitrate

and ammonium, but lower levels of phosphate (at some weeks) compared with *P. arundinacea*. The weed *Epilobium angustifolium* also had a high growth rate and was almost as efficient as *P. arundinacea* in preventing leakage of N and P. Such differences between plant species in the effect on leachate may result from higher uptake of a certain element. Alternately, plants may alter the conditions in the sludge, rendering elements less mobile (e.g., by altering pH or redox status).
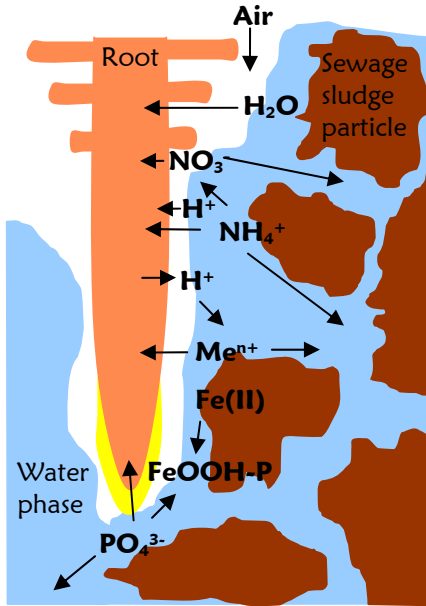

Figure 10. Processes that may occur at the interface of plant roots and sewage sludge. Water uptake by the plant increases the diffusion of air, and can thereby influence the equilibrium of nutrients and metals.

Plants taking up both ammonium and nitrate (*E. angustifolium* and *P. arundinacea*) were more efficient in preventing nitrogen leakage than those mainly taking up ammonium (*S. viminalis* and *Pinus sylvestris*) (Paper I). Most plants are able to take up N in several forms (mainly as NH_4^+ or NO_3^-, but also in organic forms such as amino acids), and are usually benefited by a mixture of species yielding a balance between negatively and positively charged molecules (Marschner, 1995). Assimilation of N from NH_4^+ is favorable for plants, since that requires less energy than using other forms, but NO_3^- is often the form that is most available (Marschner, 1995). Ideal plants for establishment in sewage sludge are those with a high and adaptive uptake of nitrogen.

   While *S. viminalis* exhibited a weaker ability to prevent nitrate leaching relative to *P. arundinacea*, the effect was reversed with regard to phosphate (Paper I). In a supplementary experiment (unpublished data), the amount of nutrients attached to the roots of these plants was examined, after growth in filter pockets between sewage sludge for 48 hours. The roots were then washed in deionized water, which was filtered (<0.45μm) and analyzed for nitrate and phosphate, performed using an ion chromatograph (Dionex

ED50); and ammonium by spectrophotometry. The results showed that while the amount of attached nitrate was higher on the roots of *P. arundinacea*, roots of *S. viminalis* had higher amounts of attached phosphate (Table 5). It is possible that plants with a high uptake of certain nutrients also have a great ability to attach these nutrients to the roots, and thereby prevent their leaching.

Table 5. Levels of nutrients in the root-washing medium; number of root tips per g DW biomass; root biomass of *Salix viminalis* and *Phalaris arundinacea* (n=6, ± SE (unpublished data). Letters indicate significant differences (p<0.05) between the plants.

	S. viminalis		*P. arundinacea*	
NH_4-N (mg g^{-1})	2.2	±0.4[a]	3.1	±1.3[a]
NO_3-N (mg g^{-1})	4.3	±0.5[a]	7.8	±0.5[b]
PO_4-P (mg g^{-1})	0.30	±0.08[b]	0.03	±0.02[a]
Number of root tips (g^{-1})	710	±110 [a]	140	±10 [b]
Root biomass (g DW)	0.16	±0.04[a]	0.14	±0.05[a]

The architecture of the root system is also likely to have an effect on the nutrient uptake. Counting the number of root tips showed that *S. viminalis* had significantly more root tips per root DW than *P. arundinacea* (Table 4). This may explain the higher capacity for phosphate *uptake* in *S. viminalis*, since many nutrients are taken up in the vicinity of the root tips (Marschner, 1995), where the suberinized layers in endodermis and exodermis have not yet developed. Nitrate, on the other hand, is taken up throughout the entire root of plants (Guo et al., 2001). This could explain the robust ability of *P. arundinacea* to reduce nitrate leakage, compared to *S. viminalis* (Paper I), despite a lower number of root tips per unit biomass (Table 4). Grasses have, furthermore, been found to have higher N:P ratios than other plant types (Eckstein and Karlsson, 1997). Therefore, grasses should be suitable for filtering N rather than P, while *S. viminalis* could be more useful if the goal is to reduce the release of P.

Results obtained from greenhouse studies in small containers, or in hydroponic solutions, will quite likely differ from the results obtained during complex field conditions, as has been found by e.g., Stoltz and Greger (2002). Preliminary studies were performed to evaluate the effect of vegetation on pore water in sewage sludge in the field (unpublished data), as an indication of what was available for leaching. Pore water was collected by vacuum suction into soil moisture samplers (MacroRhizon, Eijkelkamp, Netherland), 9 cm long and 4.5 mm wide, composed of a porous inert material. The soil moisture samplers were placed in sludge planted with either 1) *P. arundinacea*, 2) a grass mixture (Svalöf Weibull road slope mixture), 3) weeds from natural succession (mainly *E. angustifolium* and *S. myrsinifolia*), or 4) no vegetation, at the mine tailings impoundment at Gillervattnet, Boliden (Fig. 4). We also included sludge that had been applied annually (0.5 to

3 years before the study), and which had been planted with *P. arundinacea*, to determine whether the duration of sludge exposure to field conditions had an effect. Samples were taken in spring and in autumn and analyzed for pH and levels of ammonium, nitrate and phosphate.

Establishment of vegetation did not cause any significant effects on the composition of the pore water (not shown). Instead, the season at which sampling was performed, and the age of the sludge influenced the pH and nutrient concentrations (Fig. 11).
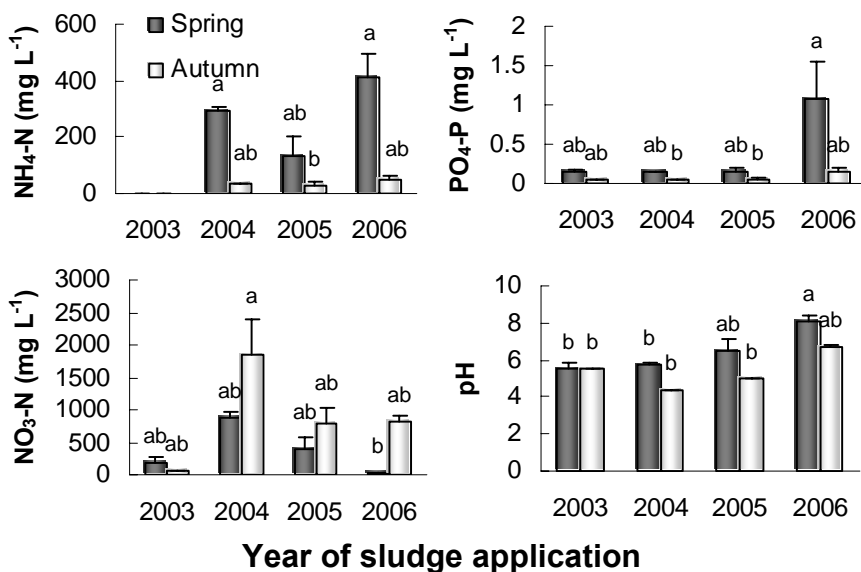

Figure 11. pH and concentrations of ammonium, nitrate and phosphate in pore water collected during the spring and autumn (31 May and 3 Oct) in 2006, from sewage sludge that had been applied annually from 2003 to 2006. The sludge was planted with *Phalaris arundinacea* (n=3, +SE) (unpublished data). Bars with different letters (a-b) differ significantly ($p < 0.05$) from each other.

While ammonium and phosphate levels were highest in newly applied sludge, and decreased over the course of the season, there were indications that nitrate concentration increased both over the course of the season and with the age of the sludge. The pH decreased with time, indicating that a nitrification process was occurring, transforming ammonium into nitrate, and releasing protons (Merrington et al., 2003).

Nitrate levels were high in the pore water of sludge obtained from the field (Fig. 11) and in leachate collected in the greenhouse (Paper I), far exceeding the water quality threshold value (NO_3-N > 50 mg L^{-1}) of the European Commission nitrate directive (91/676/EEC) (CEC, 1991b). The concentrations of phosphate were, on the other hand, low in all experiments, remaining below the water quality threshold of the urban wastewater treatment directive (91/271/EEC): 2 mg L^{-1} (CEC, 1991a).

Neither field nor greenhouse experiments tell us how much will actually leach from a complete system with sludge, fly ash and tailings. The materials below the sludge will affect what will leach; therefore leachate should also be collected at the outlet of the mine waste disposal site. Indications of how combinations of the materials affected the leachate were, however, obtained in the leachate study presented in Paper II. The presence of fly ash and mine tailings had an impact on the leakage of nutrients from the sludge. The presence of fly ash, for instance, decreased the concentrations of ammonium, nitrate and phosphate, at least when plants were also present (Paper II). In a study of waste water sludge stabilization, fly ash demonstrated strong nitrate- and phosphate-adsorbing capabilities (Topaç et al., 2008). Mine waste has, moreover, been found to bind nutrients from nutrient-rich materials and to prevent leaching (Santibáñez et al., 2007; Wei et al., 2008), even though no such effects were observed in our study (Paper II).

Although other factors than plant establishment seem to have a larger impact on leaching of N and P in the field, the greenhouse studies indicate that plants can influence the leakage of nutrients. Fast-growing plants with the ability to use both ammonium and nitrate seem to be the most suitable for establishment, in order to prevent early leaching.

4.1.4 Leakage of metals

Sewage sludge, fly ash and mine tailings contain high levels of many metals (Table 1). However, it is generally not the total metal content in a medium that predicts the availability and subsequent risk of leaching, but rather factors such as pH and the levels of organic matter and Al, Fe, and Mn oxides (Basta et al., 2005). Plants can greatly affect the conditions in the growth substrate (Gregory, 2006), and may therefore influence metal leaching.

When grown in sewage sludge, with no underlying layers of fly ash or mine tailings, different plant species (Fig. 5) displayed varying ability to affect metal leaching (Paper I). *Phalaris arundinacea* was most efficient in preventing leakage; *Pinus sylvestris* was least efficient. Even though *P. arundinacea* exhibited lower uptake of Cd and Zn, and similar water uptake rate compared with *Salix viminalis*, the former plant was more efficient in preventing leakage of metals (Paper I). In the study of attachment of nutrients to roots (unpublished data, described in chapter *4.1.3 Leakage of nutrients*), also the metal (Cd, Cu and Zn) content in the root-washing medium was analyzed. From these data we found that *P. arundinacea* had significantly higher amounts of Cd and Zn attached to the roots (per dry weight) than what *S. viminalis* had, while there was no difference concerning Cu. As previously discussed regarding N and P, it is possible that an ability to attach metals to the roots also results in a high capacity to prevent leakage of the elements. To further study absorption of metals, we analyzed root cation

exchange capacity (root CEC) of the plants. This is a measure of the number of negatively charged sites in the pectin in cell walls, acting as exchange sites for positive ions from the soil solution (Haynes, 1980). A higher root CEC has been suggested to result in higher uptake of cations in certain plants (Han et al., 1998). However, the relationship is complex; root CEC may vary with plant age, nutrient content (Heintze, 1961; Bakker and Nys, 1999), and metals (Greger and Landberg, 2008) in the growth medium. In Paper I, positive correlations were found between root CEC and total amounts of leached metals, but not with the plant uptake of metals. Theoretically, a plant with a high root CEC and therefore a robust ability to liberate metals from the substrate could also increase the leakage of metals, if the uptake of metals in the plant does not correspond to the amount mobilized from the sludge.

Combining sewage sludge, fly ash and mine tailings will make leaching behavior more complex. Several studies have shown that fly ashes can prevent metal leaching from mine waste through physical and chemical mechanisms involving coating of pyrite grains with metal precipitates (Pérez-López et al., 2007) and alkalinization, as well as by adsorption of metals to Al and Fe (hydro)oxides (Kumpiene et al., 2007). In Paper II, the leaching of metals was studied in mine tailings covered with a thin and porous layer of fly ash, covered with sludge, with and without plants. The presence of plants yielded high levels of metals in the leachate; no preventive effect of fly ash was observed. The porous layer of fly ash did not prevent root growth into the mine tailings, which could start weathering after increased access of oxygen due to water uptake by plants. Instead, the fly ash seemed to increase plant growth, resulting in greater water uptake by plants and increased weathering of the mine tailings than if no fly ash was present.

The effect of sewage sludge on metal leaching from mine tailings varies among different studies and seems to depend on site-specific conditions. Preventive effects are sometimes found. These have been related to the prevention of oxygen diffusion to mine tailings (Peppas et al., 2000), binding of metals (Holtzclaw et al., 1978), or stimulation of sulfate-reducing bacteria, producing pyrite on which metals can precipitate (Gibert et al., 2004). However, addition of sludge can also increase the mobilization of metals, by providing ligands in form of organic acids (Ribet et al., 1995), or humic and fulvic acids, which may become mobilized from FeOOH with increasing pH (Weng et al., 2007). The high nutrient content of sewage sludge can, furthermore, stimulate iron-oxidizing bacteria under aerobic conditions and thereby increase pyrite oxidation (Cravotta, 1998).

In Paper II, the effect of placing either sludge or fly ash in direct contact with the mine tailings was investigated over a time period of three months. During this time, there was no difference in metal release between these two treatments. However, as compared to uncovered mine tailings, both treatments significantly decreased leakage. Plant (*P. arundinacea*) growth decreased the amount of leachate, but did not affect the concentrations of met-

als in the leachate (Paper II). This implies that leakage may occur during the winter season following diminished plant growth and water uptake.

In summary, different plants vary in their ability to prevent metal leakage from sewage sludge (Paper I). This variation was mainly related to plant uptake of water. If a sealing layer is used that cannot prevent root growth, fast-growing plants may increase the access of oxygen to mine tailings and release of metals (Paper II). Constructing a sealing layer that is resistant to growing roots will prevent weathering of the mine tailings.

4.2 Root penetration of sealing layers

4.2.1 Plant growth in fly ash

Fly ash in a concentrated form generally harms plants, due to high levels of salts (Giordano et al., 1983), boron (Wong et al., 1998; Gupta et al., 2002), metals (Tripathi et al., 2004), or high alkalinity (Paper III, Gupta et al., 2002). However, fly ash also contains most essential elements for plant growth, except nitrogen, and can have positive effects on plants after becoming stabilized. Stabilized fly ash has been recommended for use in forestry, especially in acidic soils (Naylor and Schmidt, 1986), where it can increase available P, Ca, Mg, K and B, as well as decrease toxic effects of Al and Mn by raising the pH (Demeyer et al., 2001).

During stabilization, the fly ash becomes hydrated and carbonated, processes that turn reactive CaO and $Ca(OH)_2$ into $CaCO_3$, decreasing the alkalinity. We have been able to show that aging of hardened fly ash for ten months clearly made it less toxic toward plants, as compared with fly ash that was hardened for one week (Paper III). Plants could not grow into fresh ash, even in porous layers, while aged ash prevented root growth only when hardened to a high density.

It is difficult to determine which factor has the most adverse effect on root growth, in part due to variability among plant species. In the greenhouse test of root penetration, presented in Paper IV, *Pinus sylvestris* had a higher shoot biomass after growth on top of the metal-rich MSW fly ash, compared with growth on an alkaline biofuel fly ash; the opposite was true for *Epilobium angustifolium* and *Salix myrsinifolia*. This indicates that *P. sylvestris* has a high sensitivity toward alkalinity, while the other two species are more sensitive toward high metal levels. The fourth plant tested, *Phalaris arundinacea*, exhibited high growth in all treatments, but also displayed morphological signs of stress in all ashes, such as stunted roots with enlarged cortex, deformed cell walls and deformed root hairs (Fig. 13, Paper IV). Reduced root elongation is a sign of stress due to mechanical impedance (Bennie, 1991); however, since roots were stunted even in the ash layers with low

penetration resistance (Paper IV), the effect is more likely to be due to chemical parameters, such as alkalinity, or high levels of metals or salts.
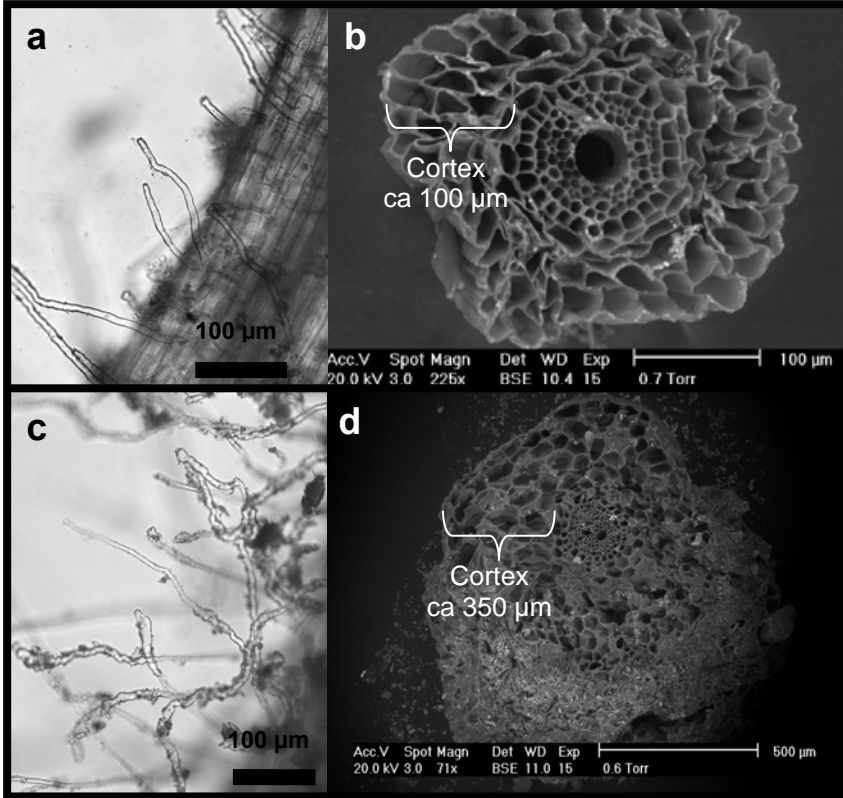

Figure 13. Root hairs and cross-sectioned roots of *Phalaris arundinacea* after growth either in a sand/clay mixture (a, b) or in biofuel fly ash (c, d). Note the disturbed growth of cell walls and root hairs (c), and increased cortex diameter (d). The roots were examined using light microscopy (a, c), and ESEM (environmental scanning electron microscopy) (b, d) (Paper IV). (Photo: Clara Neuschütz).

Most likely, the combination of stress factors caused a so-called stress-induced morphogenic response. This has been described to include a) inhibition of cell elongation, b) localized stimulation of cell division and c) alteration in cell differentiation status (Potters et al., 2007). The theory is that many stressors at sub-lethal levels induce a similar growth pattern – where the tap root is inhibited and lateral roots are stimulated. This is a strategy to avoid unfavorable soil, due to either chemical or mechanical stress, or a deficiency of nutrients. Important signals in this response are ROS (reactive oxidative species) and phytohormones, particularly auxin (Potters et al., 2007). By measuring the activity of stress-induced enzymes, such as peroxidases, stress can be analyzed in plants before growth is affected (Van Assche and Clijsters, 1990). In a comparison of the effects of weak extracts from a

metal-rich MSW fly ash and a biofuel fly ash on plants (*P. vulgaris*), the MSW ash gave rise to much higher activity of certain stress-related enzymes in the shoots (Paper III). Thus, as alkalinity decreases (in this case by dilution of the ash extract), a high content of metals may obstruct root growth. In the long term, however, the levels of available metals will decrease, leaving mechanical resistance as the most important factor in preventing root growth.

4.2.2 Penetration resistance of fly ash layers

Since the sealing layer aims to prevent diffusion of oxygen down to the tailings, it is of great importance that roots are not penetrating this layer. This became obvious in the two experiments presented in Paper II, using either a compacted or a porous layer of fly ash between the mine tailings and the covering sewage sludge. The porous fly ash could not prevent roots from growing into the mine tailings, where they caused desiccation, weathering of the mine tailings and metal release (Paper II). Non-stabilized fly ash can prevent root growth, by acting toxic due to high pH, metal or salt content, as discussed in the previous chapter. However, as reactivity decreases with time, the strength of the ash layer instead becomes crucial for the growth of the roots (Paper III).

Generally a penetrometer resistance of 2-3 MPa is considered to prevent plant root growth (Swedish Environmental Protection Agency, 1999). However, additional factors like soil particle size and structure are important; values ranging between 0.8 MPa and 5.0 MPa have been found to restrict root growth (Bengough and Mullins, 1990). In Paper IV, the aim was to find out which penetration resistance is needed in a sealing layer of fly ash to prevent root penetration. Although the ability to penetrate the fly ash layer varied with the plant species, roots were in general prevented if the mechanical resistance exceeded ~1.5 MPa (Paper IV). Nevertheless, small amounts of roots were found, especially of the grass *Phalaris arundinacea*, in the surface layer of ash layers with resistances of ~5 MPa. These roots seemed to have grown into pores or cracks in the fly ash, which is a common manner of root growth in compacted soils (Dexter, 1986; Nicoullaud et al., 1994). When a root meets compacted soil, and cannot change direction, it will decrease its growth rate by reducing both production and elongation of its cells (Bennie, 1991). Simultaneously, the width of cortex cells will increase (Bengough et al., 1997), and thereby also the root diameter (Bennie, 1991; Materechera et al., 1991). Roots of *P. arundinacea* found in fly ash often had increased diameters, and demonstrated coiled growth into pores (Paper IV). By increasing its turgor pressure, the root can grow and penetrate compacted soils (Materechera et al., 1991). Such forces exerted by the grass roots may have been involved in loosening the fly ash, since in many cases the upper

surface of well-cured fly ashes was partly pulverized where roots were present (Paper IV).

From the field observations, it was clear that the formation of an impermeable sealing layer is not limited to fly ash with a high curing ability (Paper IV). A soil profile study of the dry cover at the test plots at Boliden mine tailings impoundments showed that the fly ash had not cured well three years after application. However, in the ~80 cm deep sealing layer, various layers had formed, with a cementitious hard pan layer 5 to 15 cm below the ash surface. No roots were found growing through this layer, but roots were found growing extensively in the porous ash layer above. In a parallel test plot where sludge was mixed with fly ash in the sealing layer, no hard pans were observed, and plant roots were found down to 25 cm in the sealing layer (unpublished data). In a greenhouse study (Paper III), addition of sludge to the fly ash also increased penetration of plant roots, probably because it increased the amount and availability (by lowering the pH) of nutrients (Paper III), and decreased the bulk density of the material. In other studies, the combination of fly ash with inorganic or organic nutrients has formed substrates supporting plant growth (Pillman and Jusaitis, 1997; Cheung et al., 2000). Thus, even though addition of sewage sludge to fly ash in the sealing layer may have other beneficial effects, it should be avoided in order to prevent root penetration of the layer.

4.2.3 Plant loosening effects on cured fly ash

Fly ash exposed to outdoor conditions will start weathering: minerals, such as ettringite and calcite, which are important for the strength of the fly ash may dissolve (Steenari et al., 1999). Carbon dioxide in the air has a documented effect on fly ash, causing decreased pH and decalcification (Ecke, 2003). Since plants can both affect pH and release carbon dioxide from their roots, they theoretically could be able to affect the stability of a fly ash layer. When *Phalaris arundinacea* had been growing for 8 months on top of hardened fly ash, roots had been able to grow down into the fly ash and loosened the surface of the ash (Paper IV). The same was observed by Greger et al. (2006) in a greenhouse experiment lasting for 1 year, with various plant species growing in sewage sludge on top of cured fly ash. In that study a porous surface of the ash was found only below roots of *P. arundinacea* but not of *Betula pubescens*, *Epilobium angustifolium*, *Picea abies*, *Pinus sylvestris*, *Salix myrsinifolia*, or *Tussilago farfara*. Analysis by XRPD (X-ray powder diffraction) of the loosened fly ash in Paper IV indicated that the roots had caused weathering of some minerals. While the content of the highly resistant mineral quartz was higher in rhizosphere ash than in bulk ash, the opposite was true for calcite (in biofuel fly ash) and gypsum (in MSW fly ash) (Paper IV). This effect is possibly connected with the ability of roots to re-

duce pH (Paper III); the roots may have speeded up a process that otherwise would have occurred abiotically. However, the effect can also be a result of exuded substances that changed the mineralogy of the fly ash.

Roots exude substances as a response toward various environmental conditions (Neumann and Römheld, 2000). To decrease the frictional resistance between root and soil, root cap cells are continuously produced and sloughed off (Bengough et al., 1997), and the exudation of carbohydrates from the root has been shown to increase with increasing mechanical impedance (Barber and Gunn, 1974; Groleau-Renaud et al., 1998). Analysis of saccharide content in root exudates from *P. arundinacea* growing toward ash layers of various strengths, however, did not reveal any such response (Paper IV). Instead the exudation of saccharides seemed to increase if the roots were exposed to a metal-rich fly ash as compared with a more alkaline fly ash.

The composition of root exudates is affected by many factors, including nutrient availability (Marschner, 1995). Weathering of minerals can be significantly increased by the activity of growing roots, which has been connected with changes in elemental concentrations and pH, as well as exudation of chelating substances (Hinsinger et al., 2001). Dissolution of minerals, in particular secondarily formed minerals, is often associated with the presence of organic acids (Hinsinger et al., 2001; Ryan et al., 2001; Reichard et al., 2005). Organic acids found in manure have been found to exert a dissolving effect on cement (Bertron et al., 2005). The penetration resistance of hardened fly ash was, however, not influenced by addition of a mixture of organic acids, but was affected by addition of a mixture of monosaccharides (fructose and glucose) (Paper IV). When ash has been mixed with cellulose, iso-saccharinic acid has been formed (a degradation product of cellulose), and increased the mobility of metals (Wikman et al., 2003). Furthermore, saccharides are known to retard the curing of concrete (Garci Juenger and Jennings, 2002), and can prevent formation of ettringite, possibly by chelating Ca (Cody et al., 2004). Since the fly ashes we tested were cured for only one week before the solutions were added (Paper IV), they probably were still reactive, and the saccharides may have prevented the growth of crystals. However, the effect of the saccharides may also have been indirect, since the solutions were not sterile; microorganisms may have used the saccharides and exuded other compounds affecting the fly ash (Fig. 14). Microorganisms can cause dissolution of minerals in a number of ways (Sand, 1997), and are attracted to root surfaces, especially following increased root exudations, for instance due to growth in compacted soils (Ikeda et al., 1997).

Further studies under axenic conditions could highlight the effects of different substances on cured fly ash; however, since field conditions are never sterile, it is important to understand the effects of complex systems with both roots and associated microorganisms.
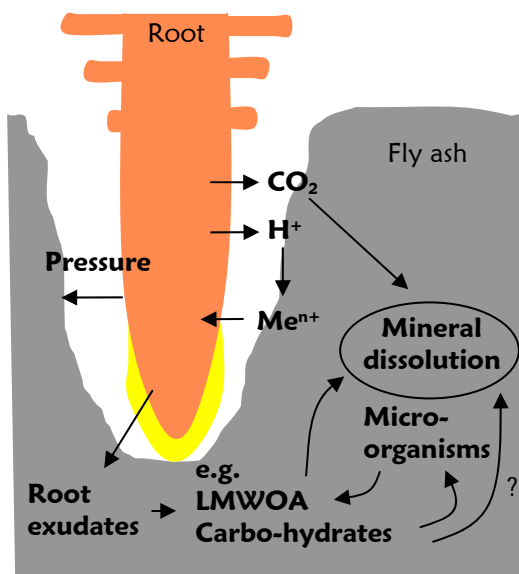
Figure 14. Schematic illustration of possible impacts of plant roots on cured fly ash. LMWOA= low molecular weight organic acids.

4.3 Long term function and choice of plants

The time frame of the studies presented in this thesis extended over the course of days to several months, complemented by observations in the field of vegetated dry covers with ages of up to eight years (Paper IV). The results should, therefore, be used for assessing short-term performance of vegetated covers containing fly ash and sewage sludge.

The leaching of nutrients and metals will probably cease with time; however, the duration of this process is difficult to predict. In the greenhouse study (Paper I), the release of nitrogen decreased within 2.5 months. In the field study (unpublished data), there was a trend toward decreasing levels of ammonium and phosphate, but not of nitrate, in sludge pore water during the summer seasons (Fig. 11).

Construction of the dry cover is of great importance. Whether sludge or fly ash is placed in direct contact with the tailings seems, however, not to be as important as the compactness of the sealing layers. Layers that are too shallow and porous will increase the risk of desiccation, crack formation, root penetration and oxygen diffusion into the mine tailings. The depths of sealing layers used in the field tests (0.5 to 0.8 m) seemed to be sufficient to prevent root penetration. The fly ash used should have robust curing ability; however, precipitation processes under outdoor conditions may cause cementitious layers even in fly ashes with weak curing ability (Paper IV). Therefore, such ashes should not be disregarded until more results concerning their long-term function have been obtained. The protective cover of

sludge should be at least 0.5 m, since application of a thinner layer may desiccate before plants have established properly, and the layer may lose its protective function. The sludge will be degraded with time, but will eventually be replaced by organic matter from the vegetation (Bendfeldt et al., 2001). Since trees will disperse to the area, sooner or later, the protective cover needs to be thick enough to support roots of large trees (Table 2). Scars in the cover caused by trees felled by the wind may occur, but if the ash sealing layer is compact enough to prevent root growth, it should also remain intact even after a local removal of the protective cover; with time a new organic layer may form on that spot. To keep the ash sealing layer resistant over a long period of time and prevent root growth, no or little sludge should be added, as observed previously in a study of waste product degradation (Fang and Wong, 2000).

The plant species used in the experiments displayed varying ability to establish in sewage sludge, to prevent nutrient and metal leakage and to grow into ash sealing layers (Table 6).

Table 6. Experiences from experiments with various plant species. Where there is no reference, data is presented in the summary of the thesis.

Plant species	Experimental observations	Paper
Grasses		
Agrostis capillaris	Low germination rate in sludge	
Phalaris arundinacea	Vigorous growth in sludge, high ability to prevent nutrient leakage and to grow into ash layers	I, II, III, IV
Poa pratensis	Low germination rate in sludge, moderate growth into ash layers	III
Herbs		
Cannabis sativa	Vigorous growth in sludge and shallow root systems	III
Epilobium angustifolium	Vigorous growth in sludge, high ability to prevent nutrient leakage, little root growth into ash layers	I, IV
Phaseolus vulgaris	Sensitive toward ashes rich in metals and salts	III
Pisum sativum	Sensitive toward alkaline ashes	
Tussilago farfara	Vigorous growth in sludge	
Trees and shrubs		
Betula pendula	Low germination rate in sludge. Low root growth into ash layers	III
Picea abies	Medium growth in sludge	
Pinus sylvestris	Low ability to prevent elemental leakage from sludge, and moderate growth into ash layers	I, III, IV
Salix myrsinifolia	Vigorous growth in sludge, low growth into ash layers	IV
Salix viminalis	Sensitive toward fresh sludge. Moderate ability to prevent elemental leakage from sludge. High growth into ash layers	I, III

Favorable plant species for a rapid establishment in sewage sludge are those that can be dispersed by seeds. Plants spread by natural succession may have a preventive effect on leakage (e.g., *E. angustifolium*), but will become established more slowly than a manually introduced plant. The energy grass *P. arundinacea* exhibited vigorous growth in sludge in a temperate climate over several seasons and was efficient in reducing leakage of both nutrients and metals and is, therefore, a good option. However, this plant demonstrated a strong ability to grow into sealing layers of fly ash (Paper IV). The protective layer must, therefore, be deep enough to support the root system of this plant, and trees that will establish later on. Alternately, fast growing grass species with shallower root systems should be chosen. *Salix* species may be less suitable, since some of the species exhibit high metal uptake to the shoots and restricted ability to prevent the release of nutrients and metals, at least in the short term (Paper I). An introduction of various plant species would, on the other hand, be beneficial, since they then can complement each other with varying efficiencies in the uptake of different nutrients, as discussed in Paper I and by Marschner (1998).

5 Conclusions

The general conclusion from the work presented in this thesis is that certain plants may be efficient in phytostabilization of mine tailings covered with fly ash and sewage sludge. Fast-growing plant species showed good potential in reducing the leakage of N, P and metals. However, some plants were physiologically stressed, could not decrease the leakage from the sewage sludge, or had an impact on the mineral structure of the sealing layer. The correct choice of plant species is, therefore, of great significance. Moreover, the sealing layer needs to be compact enough to prevent the penetration of plant roots, and the protective cover deep enough to provide enough space as well as nutrients and water for the root systems to develop. More specific conclusions, related to the aim of the thesis, are as follows:

1.   *Establishment of plants in sewage sludge and their effect on leakage of nutrients and metals.*

    a.   A range of plant species can successfully establish in sewage sludge even in a temperate climate. Ruderate plant species with wind-dispersed seeds, such as *Epilobium angustifolium* and *Salix* spp., grew vigorously within one year in areas left for natural succession. Among the introduced plants, seed-dispersed grasses were more efficiently established than perennial plants that were transferred as cuttings. However, in fresh sludge most plants did not germinate, probably due to high levels of ammonium and salts. Aeration of the sludge or addition of bark improved the early establishment.

    b.   Plants decreased leaching of nutrients and metals mainly by decreasing the amount of leachate formed, but also by decreasing the concentrations of elements. A high water uptake rate resulted in reduced leakage of most elements. However, if roots were able to grow through the sealing layer of fly ash down to the mine tailings, high water uptake caused desiccation of the mine tailings and enhanced metal release. Plants with an ability to take up N both as nitrate and ammonium (*Phalaris arundinacea* and *Epilobium angustifolium*) were more efficient in preventing N leakage than those taking up primarily ammonium (*Salix viminalis* and

Pinus sylvestris). Fast-growing plants could neutralize pH in leachate from sludge. However, the initial drop in pH and high N leaching could not be counteracted by any of the plants used, and plants did not affect pore water chemistry in field experiments. Instead, seasonal variations had a larger impact.

c. Metals primarily accumulated in the roots of plants growing in sewage sludge, while the translocation to shoots was moderate. Hence, the risk to grazing animals seemed negligible. However, shoots of *S. myrsinifolia* contained levels of Zn exceeding the threshold levels for animal feed.

2. *Root penetration of sealing layers containing fly ash.*

a. Plants respond negatively toward fresh fly ash, due to a combination of factors. Alkalinity strongly inhibits growth in many plants, while less alkaline ashes induced stress responses in plants due to high metal and salt content. In ash extractions with pH values up to 12, plants could decrease the pH, provided that the alkalinity was not too strong.

b. When the reactivity of the ashes decreases, root growth is instead inhibited by high mechanical impedance of the material. Plant roots were in general prevented from growing into an ash sealing layer if the penetration resistance exceeded ~1.5 MPa. However, small amounts of roots, in particular of *P. arundinacea*, grew into the surface of ash layers with higher penetration resistances. Addition of sludge to the fly ash increased the risk of root penetration. Preferably, fly ash with strong curing ability should be chosen when constructing the sealing layer. Nevertheless, ashes with weak curing ability can prevent root growth, if cementitious layers (hard pans) are formed in the sealing layer.

c. Root growth had an impact on the mineralogy of cured fly ash and increased the weathering rate of secondary minerals, such as calcite and gypsum. Exudation of organic compounds, such as monosaccharides, may have an impact on the penetration resistance of a fly ash sealing layer.

6 Future work

To optimize the use of plants in the stabilization of mine tailings covered with sewage sludge and fly ash, the physiological responses to these materials should be further examined. The exudation of substances from roots by plants confronted with a sealing layer of fly ash should be investigated, with regard to the composition of different ashes, as well as the plant species used in the remediation and their effects on the ash layer. Furthermore, the effects of plant roots on already-weathered ash layers, or degraded sewage sludge, should be investigated, as well as the ability of different plant species to utilize nutrients present in the sludge.

The investigations performed within the research for this thesis have in general been focused on more short-term effects, which are those discovered during the first months after application of a cover material and the establishment of plants. Most work has, furthermore, been conducted under greenhouse conditions with plants growing in monocultures in small containers. To verify the data obtained, long-term studies should be performed, with larger lysimeters or in the field. Further, leakage water should be collected from complete systems, containing all cover materials, as well as vegetation, at points where the leachate is of concern.

Additional knowledge about the root penetration of old sealing layers is necessary if we are to fully understand the effects of different types of vegetation on dry cover performance. The purpose of the dry cover is to encapsulate the mine tailings for as long as possible. During plant succession, trees will establish and soil-forming processes will occur, rendering long-term studies necessary.

Sammanfattning på svenska

Växter har en förmåga att anpassa och etablera sig i de flesta typer av jordar, och kan också påverka förhållandena i jorden. På många platser används växter för att stabilisera jord som annars skulle erodera, eller för att immobilisera, ta upp eller bryta ner föroreningar, metoder som gemensamt kallas för fytoremediering. Med en ökande medvetenhet om vad föroreningar kan orsaka ökar också kraven på att industriella restprodukter tas om hand på ett hållbart sätt, samtidigt som produktionen av avfall ökar.

Ett exempel på avfall som kräver stora deponeringsytor är sulfidrik anrikningssand från utvinning av metaller. Denna finkorniga sand måste täckas över för att inte börja vittra och släppa ifrån sig ett surt metallhaltigt läckagevatten som är giftigt för många organismer. Eftersom deponierna är stora krävs enorma mängder täckningsmaterial, och man utvärderar därför möjligheterna att använda andra restprodukter för detta syfte.

Två produkter som också produceras i stora mängder och kräver omhändertagande är flygaska från värmeverk och rötslam från avloppsreningsverk. Flygaska har fördelen att det kan härda ungefär som cement, och har låg nedbrytningshastighet, och därför skulle kunna forma ett hållbart tätskikt som förhindrar syre och även växter och djur att ta sig ned och påverka gruvavfallet. De flesta flygaskor har dessutom ett högt pH, vilket skulle kunna motverka bildning av surt läckagevatten. Rötslam har länge delvis använts inom jordbruket på grund av sitt höga näringsinnehåll, men en rädsla för överföring av ohälsosamma kemikalier till livsmedel har gjort att denna användning har minskat. På gruvavfall skulle slammet kunna blandas med flygaska till ett tätskikt, eller läggas ut som skyddsskikt ovanpå tätskiktet, som substrat för växtetablering. För att skapa ett täckskikt med lång hållbarhet bör dock förhållandevis tjocka skikt anläggas, med följden att stora mängder aska och slam sprids ut. Frågan är vad som händer när växter etablerar sig – hur kan de påverka läckage av näring och metaller från slammet, och kommer rötter att kunna växa ned i ett tätskikt av härdad aska? Dessa är huvudfrågorna för denna avhandling, och svar har sökts genom ett antal försök både i fält, växthus och laboratorium.

Resultaten visar att växter kan etablera sig väl i ett täckskikt av rötslam, även om groning i färskt slam kan vara problematiskt. Växterna kan förhindra läckage av föroreningar, men också öka läckaget om tätskiktet är för tunt. Effekten varierade även mellan olika växtarter. Det initiala läckaget av kväve visade sig kunna vara högt från rötslammet, men kan dämpas

framförallt om snabbväxande växer används med en god förmåga att ta upp nitrat, ett näringsämne som är mycket lättlösligt. Framförallt kunde växter förhindra läckage genom att ta upp vatten, och därmed minska mängden bildat läckagevatten. Efter en initial insådd av gräs bör ett behandlat område kunna lämnas för naturlig succession som tillåter att en blandning av växtarter, i och med att olika arter visade potential att minska läckage av olika ämnen, och kan därför komplettera varandra. Introduktion av snabbväxande energigrödor är ett möjligt alternativ. Energigräset rörflen förhindrade effektivt läckage av näring och metaller, men hade också en förmåga att tolerera och växa ned i härdad flygaska, och kräver därmed ett tjockt täckskikt. Korgvide, som också används som energigröda ("*Salix*"), hade sämre förmåga att etablera sig i slammet och förhindra tidigt läckage av kväve.

Nyhärdad flygaska är reaktiv, och kan förhindra rotväxt genom högt pH, och innehåll av metaller och salter. När askan har stabiliserats och pH sjunkit är dock hårdheten i askan avgörande för om rötter växer ned eller inte. Ett penetrationsmotstånd över ~1.5 MPa räckte i allmänhet för att stoppa rotväxt ned i askan, men små mängder rötter återfanns i ytan av asklager med högre hårdhet. Rötterna, eller till dem associerade mikroorganismer, kunde påskynda vittringen av mineral i askan, och anses därmed kunna påverka hållbarheten i askan. Denna effekt är förmodligen dock liten jämfört med vad abiotiska faktorer orsakar ute i fält. Observationer i fält visade att två asktätskikt effektivt förhindrade rotväxt på olika sätt. Den ena askan hade härdat mycket väl, och stoppade totalt all rotväxt även av välväxta träd. Den andra askan hade härdat dåligt, men istället hade ett cementerat skikt bildats i övre delen av tätskiktet som rötter inte kunde tränga igenom.

Sammanfattningsvis visar försöken att valda växter kan användas vid stabilisering av gruvavfall med flygaska och rötslam, förutsatt att materialen läggs ut så att rötter förhindras att växa ned i gruvavfallet.

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