ENVIRONMENTAL BIOTECHNOLOGY 2 (1) 2006, 37-45

A pilot-scale example of phytoremediation in the arctic area: comparison of zones placed at different distances from a metal emission source*

Ryunosuke Kikuchi[1], Tamara T. Gorbacheva[2], Romeu Gerardo[1]

[1] Department of Basic Science and Environment (CERNAS); ESAC – Polytechnic, Institute of Coimbra, Bencanta, 3040-316 Coimbra, Portugal
[2] Institute of the North Industrial Ecology Problems – Kola Science Center, Russian Academy of Science, Fersman Str. 14, Apatity, 184200 Murmansk, Russia
Corresponding author. Tel.: (+351) 239 802287; fax: (+351) 239 802979; e-mail: kikuchi@mail.esac.pt
Keywords: arctic, copper, heavy metal, nickel, phytoremediation, willow

ABSTRACT

Biological methods for soil rehabilitation are comparatively cheap, but it is only a few years since the strategies of biological remediation were adopted. This paper therefore discusses the possibility of using the approach of phytoremediation (a biological method) for tackling heavy metal-contaminated land with harsh climatic conditions in the arctic region. A preliminary research on a pilot scale of 4 ha was carried out on territories subjected to continuing pollution load from the Monchegorsk smelter complex (67°51'N and 32°48'E in Russia) in order to investigate the feasibility of phytoremediation under a harsh climate (annual mean temperature of -1°C) and current pollution load (~450 to ~2,400 g ha^{-1} y^{-1} Ni, ~750 to ~2,700 g ha^{-1} y^{-1} Cu and other depositions): after a compost substratum was added to the contaminated land, metal-tolerant plants (willow and birch collected in the tolerance zone) were used for this research. The results obtained over 3 years showed the applied plants had good phytostabilization (i.e. the fixation of metals in chemically inert form); the Ni concentration (457.2 mg kg^{-1}) and the Cu concentration (338.3 mg kg^{-1}) in the willow leaves in the test field were 117 times and 147 times greater, respectively, than those in the background field. It is therefore indicated that Ni, Cu and other metals can be removed from metal-contaminated land by harvesting the plants (i.e. removal of annual litterfall of deciduous trees from the contaminated territory).

INTRODUCTION

According to an announcement by the United Nations Environment Program (Nairobi, 19 February 2001) (UNEP 2001), there have been massive changes in the Arctic, which are likely to have dramatic impacts on the world's weather systems, fisheries, wildlife and people living in the far north. For example, the deposition of metal pollutants is a very serious problem in the arctic region. The Kola Peninsula (66-70°N and 28°30'-41°30'E) in Russia is one of the most seriously polluted areas in the Arctic/sub-arctic regions (Nilsson 1997): close by the nickel-copper smelters, the deposition of metal pollutants has severely damaged the soil and ground vegetation, resulting in an industrial desert. Our preparatory survey indicated that the severely damaged areas around smelter complexes (Severonikel and Pechenganikel) may exceed ~20,000 ha, and it seems impossible to restore these areas without a great amount of financial aid. Current engineering-based technologies used to clean up soils – like the removal of contaminated topsoil for storage in landfills – are very costly (ARS 2000); in contrast, biological methods are comparatively cheap (Semple et al. 2001). However, it has been only a few years since the strategies of biological remediation were adopted (Semple et al. 2001). As a result, there is a lack of general information as well as a limited number of pollutants (or pollutant matrixes) treated.

One of the biological methods for environmental improvement is phytoremediation, which is defined as the use of plants (so-called "green" technology) to remove pollutants from the environment or to render them harmless. The main approaches of phytoremediation are classified into 5 types: phytoextraction, phytodegradation, rhizofiltration, phytostabilization and phytovolatilization (ARS 2000). Phytoextraction is recognized as an effective method for soil remediation in the case of a low or moderate degree of contamination; however, when the degree of contamination is high and the pollution still continues, the phytoextraction procedure will take a long time. Phytostabilization does not attempt to

---

* Presented at The First International Environmental Best Practices Conference, 07-10 August 2006, Olsztyn, Poland

extract the metals from soil, but aims to immobilize them; the metal substances added to the soil are fixed as chemically inert forms in the applied phytoremediators (i.e. metal-tolerant plants). Thus, this type of phytoremediator restrains metals from mobilizing into the surroundings. Our test field (a part of the industrial desert) had been forest land covered with dwarf shrub before the smelter operation started in 1947, and metal-related pollution is still being imposed upon the local terrestrial ecosystem. Considering this severe contamination, attention was focused on phytostabilisation. It is known that plant uptake of metals increases with an increase in the soil metal concentration and reaches an uptake maximum [plateau hypothesis (Hamon et al. 1999)]. Taking the current pollution load and the plateau hypothesis into account in our preliminary test, it can be considered that the metal content available to the phytoremediator must be more important than the fluctuant total concentration of metals in the soil.

Since bioproductivity is low in this arctic/subarctic region and the metal pollution has significantly damaged the local ecosystem, there is doubt as to whether phytostabilization can work well to tackle heavy metals under such conditions. Therefore, our preliminary field test (4 ha) aimed to verify the feasibility of phytoremediation in terms of recovering the metal-polluted land under harsh conditions.

PHYTOREMEDIATION AND BIOPRODUCTIVITY

First, basic information about the relation between phytoremediation and bioproductivity is briefly reviewed to help the understanding of our research plan, followed by the main description.

Certain plant species – known as metal hyperaccumulators – have the ability to extract elements from the soil and concentrate them in the easily harvested plant stems, shoots, and leaves. While acting as vacuum cleaners, these plants must be able to tolerate and survive high levels of heavy metals in soils – zinc, cadmium, nickel, etc. The following plants are often used (LPS 2005): duckweeds (*Lemna minor*), eucalyptus (*Eucalyptus spp*), water hyacinths (*Eichhornia crassipes*), leucaena (*Leucaena spp*), and some others, to regenerate the contaminated lands. To remediate heavy metal-contaminated soil, planted vegetation should have high biomass production. But the Arctic/subarctic region is characterized by a harsh climate, so bioproductivity is low. Figure 1 illustrates the relation between bioproductivity and the distance from the smelter complexes (Monchegorsk) (Lukina and Nikonov 1996).

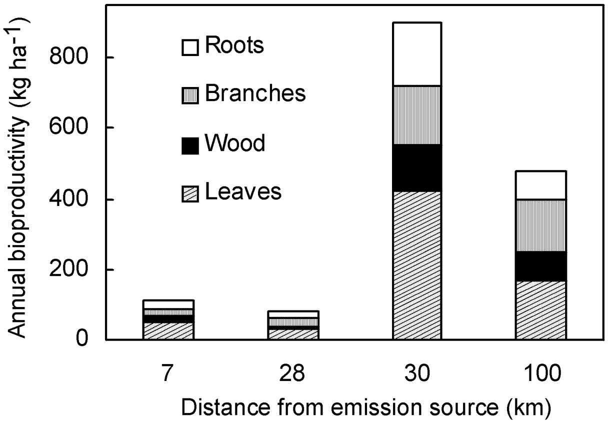


Figure 1. Relation between annual bioproductivity of birch and distance from source of metal pollution in the Monchegorsk area [redrawn from Lukina and Nikonov (1996)].

It follows from Figure 1 that there is no clear relation between the bioproductivity of birch and the distance from the emission source (the smelter complexes); hence it is necessary to consider not only the current pollution and the climatic conditions but also the local soil fertility. The most common soil type on the Kola Peninsula is Podzol, and its thickness usually does not exceed 30-50 cm (Koptsik and Koptsik 2001). The root system of vegetation growing on Podzols is located at its deepest in the top horizon. This type of soil is generally nutrient-poor (Bridges 1997). Thus small measures such as adding an artificial substratum (about 15-20 cm) and planting metal tolerant vegetation could be proposed as low cost and effective for rehabilitation of territory with initial low nutrient status. Considering the above-mentioned points, the following method is considered feasible in this region: a bulk ground is created by introducing the compost into the polluted land to improve the nutrition status and immobilize metal pollutants, and tolerant vegetation (willow and birch) is then planted. It is recognized that application of compost made from sewage sludge is effective in improving soil properties physically, chemically and biologically in agriculture and forestry (Balesdent et al. 2000; Etana et al. 1999). In other words, it was attempted to combine sewage sludge composting (issue of municipal waste) with phytoremediation (recovery of metal-polluted land) in this field test.

MATERIALS AND METHOD

In the test region (67°51’N, 32°48’E), the annual mean temperature is about 1°C, the maximum temperature (~15°C) is generally recorded in July, and snowmelt takes place during April to June. Wind is blowing during the winter period from the south and north-west, and the dominant directions during the summer period are north and south; however, upper wind direction in this area is highly dependent on the movement of low-pressure belts, and the surface winds are highly dependent on the topography and the friction imposed by the vegetation (Mäkinen 1994).

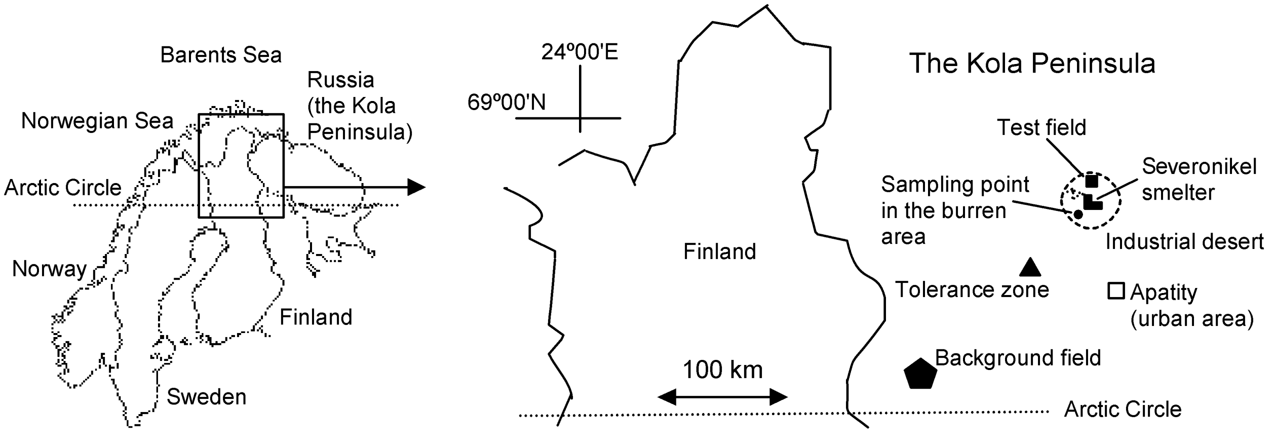


Figure 2. Location of the survey fields in the Monchegorsk area on the Kola Peninsula.

Polluted land near the “Severonikel” smelter (see Figure 2) in the Monchegorsk area on the Kola Peninsula was proposed as the location (a part of the industrial desert area ~3 km to the north of the smelter) for a phytoremediation test. As stated in the introduction, the area near the smelter has been barren since the smelter started operating, and metal pollution is still being imposed upon this area. In recent years, the smelter complexes have emitted annually ~1,500 tons of metal-containing dusts (Baklanov 1994). The territory (4 ha) chosen for the phytoremediation test was divided into 12 individual plots with random distances from one to the other. The observation territory was extended from the line 67°56’48”N 32°52’00”E and 67°56’46”N 32°51’52”E to the line 67°56’56”N 32°50’60”E and 67°56’54”N 32°50’54”E. More than 6000 deciduous trees were planted in the survey fields, and comparative observation was also carried out in each field (Figure 2): (i) *sampling plots in the industrial desert* (near the test field) – dead trees and bare ground – are situated 5 km to the south-west of the smelter; (ii) *the tolerance zone* – situated 15-30 km around the smelter showed greater soil contamination than the background plots, but deciduous trees are surviving in such conditions; and (iii) *the background site* – is situated 200-300 km to the south-west of the Severonikel smelter.

The field test consisted of the measurement of current pollution load, preparation of a compost substratum, plantation of possible phytoremediators, analysis of soil properties, and diagnosis of elements in phytoremediators. In view of the main concept (metal bioavailability) presented in the introduction, attention was given to determining the content of elements that would be available for plant uptake. In this section, *n* in brackets shows the number of measurements. The above procedure and research items are illustrated in Figure 3, and each experimental process is described below.

Current pollution load (analysis of snow)

Plots for snow sampling were randomly chosen in the background field (*n* = 6 in 2004 and 2005) located 260 km from the smelter, the rehabilitation test field (*n* = 3 in 2004 and *n* = 6 in 2005) and the industrial desert (*n* = 3 in 2004 and 2005). The precipitated snow cores were sampled with a plastic collector (i.e. plastic tube and restricting Plexiglas plate) and plastic bags in the pit wall. Each snow core was sampled in the orientation from top line to soil surface. Depending on snow density, increments varied from group to group (i.e. variation between 15-20 cm and whole profile height).

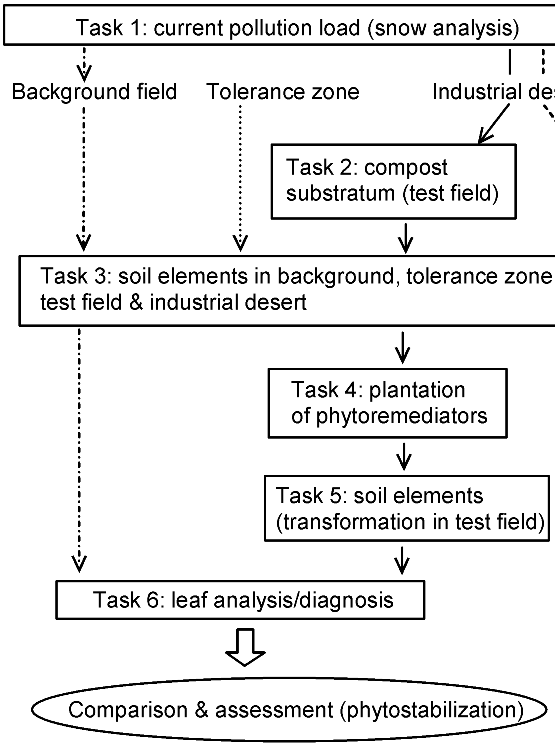


Figure 3. Schematics of the research tasks.

The precipitated snow was analyzed as a parameter of current pollution load. The samples were melted in a plastic basin in the laboratory. The volume of each sample was recorded and then measured using the following techniques – without the filtration – potentiometry for determining H^+, after filtration – atomic absorption spectrophotometry for determining Al, Fe, Ca, Mg, K, Mn, Zn, Ni, Cu, Na, Pb, Cd, Co and Sr, ion chromatography for Cl^-, SO_4^{2-} and NO^{3-}, colorimetry for determining P, PO_4^{3-}, NH_4^+ and Si, and the oxidability method using permanganate and bichromate for C determination.

Compost and artificial substratum preparation

Sewage sludge composting was carried out to prepare the artificial substratum. Freestanding piles (< 3 m height) of sewage sludge were built on level well-aerated spots, and they were occasionally turned for the purpose of material homogenization and re-oxygenation for a period of about 1 month (July to August 2003). The rehabilitation test field was bulldozed and big stones were removed, then the compost (15-20 cm layer) was introduced to the prepared fields at an application rate of 1,200 tons ha^{-1}, together with the following additives: 200 tons ha^{-1} of sawdust, and 600 tons ha^{-1} of sand. After this preparation, 2 tons ha^{-1} of dolomite was scattered on the fields.

Soil elements contained in observation fields

The sampling procedure in the presented test is summarized as follows: soil samples were taken in a background survey field ($n = 40$ in the birch forest in 2003), tolerance survey fields ($n = 45$ in 2003), and the industrial desert ($n = 11$ to 12 in 2003) for the purpose of comparative research; and when the compost (see the description of compost preparation) was mixed with dolomite to produce an artificial substratum, the first sampling was carried out ($n = 39$ in 2003). The second sampling ($n = 28$) and the third sampling were carried out in 2004 and 2005, respectively.

All soil samples were dried at room temperature and put through a sieve with a 1 mm grid. After this pre-treatment, chemical analysis was carried out as follows: (i) each element was extracted from the pre-treated sample using 1M ammonium acetate under buffer pH = 4.7 (Halonen et al. 1983), and the following elements were then determined by atomic absorption spectrometry – K, Ca, Mg, Al, Zn, Fe, Cu, Ni, Mn, Pb, Cd and Co; (ii) total nitrogen was determined by Kjeldahl digestion using H_2SO_4-K_2SO_4-$CuSO_4$ mix; (iii) phosphorous composition was also extracted by ammonium acetate under the same pH buffer, and an aliquote of the extract was then analyzed by molybdate colorimetry to determine the P content; and (iv) 10.0 g of the sieved sample was mixed with 25.0 ml of distilled water, and then the pH value of the sample was measured by the glass electrode method.

Plantation of phytoremediators

The smelter is currently operating, and the surrounding region still has smelter-related pollution; however, the existing plants (mainly deciduous trees) have withstood such pollution in the tolerance zone. Given these facts, willow and birch were used for afforestation in the autumn of 2003 after the above-mentioned artificial substratum had been prepared. Willows and birches (as possible phytoremediators) have been left untrimmed since 1995 in an abandoned farm situated within the tolerance zone, so seedlings of these trees were collected from the farm. Each seedling (~1 m height) was put in a polyethylene sack where the local soil encircled its root zone in order to protect against root dry during transplantation. The seedlings prepared in this way were carefully transported to the test field. As soon as the seedlings arrived in the test field, they were taken out from the sacks and were planted 4 abreast at regular intervals of 2 m in a 10 m – wide strip; in addition, grasses were laid in the gaps between the seedlings (free space) to facilitate soil aggregation.

Analysis of leaves

Leaves of willow and birch (as phytoremediators) were taken in the rehabilitation test field ($n = 12$ in September 2003, $n = 6$ in August 2004 and $n = 34$ in August 2005) and in the background field ($n = 12$ in September 2003).

Leaf samples were dried at room temperature, and they were digested with concentrated nitric acid to destroy the matrix and dissolve metals. Metals in a sample solution were determined by atomic absorption spectrometry, and phosphorous composition was determined by molybdate colorimetry. A quality check of plant analysis was carried out at our laboratory on the basis of the present control standards which are to be linked with the International Co-operative Program on Assessment and Monitoring of Air Pollution Effects on Forests (operated by the United Nations Economic Commission for Europe).

RESULTS

Because of the space limitations, all data are shown as the average values, which are considered to be the representative data.

Pollution load

The chemical qualities of the precipitated snow (i.e. wet precipitation of pollutants) were measured in the background field, in the rehabilitation test field and the industrial desert in order to assess the pollution load. These results are summarized in Table 1.

In the rehabilitation field, the metal load in 2005 was significantly greater than that in 2004; however, the other sites did not show this trend. The following reason is possible: the sampled volume of snow core increased from 850-1215 ml in 2004 to 1140-5700 ml in 2006 in the rehabilitation field; hence, more metal pollutants were found to be accumulated in the snow. Furthermore, increases of Cl and Na were also recorded in the

Table 1. Pollution load induced by snow precipitation: the data obtained during the period of time from September 2003 to the first week of April 2004 (abbreviated as 2004) and from September 2004 to the first week of April 2005 (abbreviated as 2005).

Element	Background field		Rehabilitation field		Industrial desert	
(g/ha)	2004	2005	2004	2005	2004	2005
P	11.7	7.6	5.5	12.0	11.7	7.4
K	80.6	104.5	74.4	518.2	131.2	91.2
Ca	614.2	577.8	1,154.3	4,375.3	1,297.2	766.2
Mg	100.2	91.2	192.5	515.5	288.4	192.1
Fe	3.2	2.2	26.7	19.0	21.1	3.4
Mn	2.4	3.3	4.7	34,8	2.3	1.8
Zn	4.5	2.4	18.4	58.1	9.2	3.4
Cu	1.2	1.1	752.6	2,695.6	70.3	28.8
Al	2.3	5.7	16.2	28.5	24.2	4.6
Ni	0.4	0.4	448.1	2,407.1	371.4	349.2
Na	282.3	346.4	340.8	11,834.7	839.6	1,066.4
Si	76.8	123.9	105.9	188.6	158.5	86.2
Sr	8.4	7.1	12.2	24.6	16.6	7.7
Cd	0.2	0.1	0.6	2.2	0.2	0.1
Pb	0.1	0.1	1.4	0.7	1.3	0.2
Co	0.2	0.1	10.8	45.7	9.1	7.7
Cr	0.2	0.2	0.5	0.2	1.1	0.1
SO_4^{2-}	1,087.7	501.7	5,667.7	21,118.5	3,009.7	2,685.5
NO^{3-}	1,034.6	657.4	554.9	429.1	1,479.3	1,138.1
PO_4^{3-}	10.0	7.5	5.5	6.7	11.7	7.3
Cl^-	610.7	892.9	789.3	25,606.6	1,861.6	2,496.8
NH_4^+	229.9	461.1	226.7	294.2	324.0	608.2
H^+	21.1	28.2	4.2	8.7	23.7	14.1
C	288.3	1,662.2	373.1	794.4	1,203.4	1,356.1

rehabilitation field; it can be considered that during winter the effects of traffic (application of anti-freezing agent in particular) increased saline in this field which is located near a road. The amounts of saline elements (e.g. Cl and Na) in the rehabilitation field were a few times greater than those in the background field; however, as seen in Table 1 (current pollution load), (i) the Cu amount in the rehabilitation test field was over ~2,400 times greater than that in the background field, and (ii) the Ni amount in the rehabilitation test field was over ~6,000 times greater than that in the background field. It is reported that the smelter is the only metallurgical plant processing Ni-Cu ores in this region and its emission mainly contains rich amounts of Cu, Ni and dusts (Mäkinen 1994). Considering the geographical condition (the rehabilitation field is quite close to the smelter, see Figure 2) and the pollution pattern (rich amounts of Cu and Ni), it is concluded that the main factor of environmental degradation (i.e. defoliation) around the nickel-copper smelter complexes is heavy-metal pollution, and the pollution load is still being imposed upon the surrounding vegetation in the rehabilitation field.

Soil elements

The total element content is generally much different from the plant-available content because the major portion of the total content is less available or unavailable to plants; for example, less than 0.01% of the total content of nitrogen generally exists as plant-available form (Woodmansee et al. 1981). As stated above, analytical attention was given to determine the element content that would be available for plant uptake. The amounts of elements extracted with ammonium acetate were simply expressed as the measured contents, and their amount can be mainly considered as plant-available form (Witting and Neite 1989). The data of measured elements were classified into 4 types for convenience and are presented in Figure 4: (i) essential elements – N, P, K, Ca and Mg; (ii) microelements – Fe, Mn, Zn and Cu; (iii) other metals – Al and Ni; and (iv) trace metals – Cd, Pb and Co.

Based on the measured soil properties, Figure 4 compares soil parameters in each field – background field, tolerance zone, compost substratum (remediation test field) and industrial desert; the great amount of Cu in the industrial desert can be read from this figure.

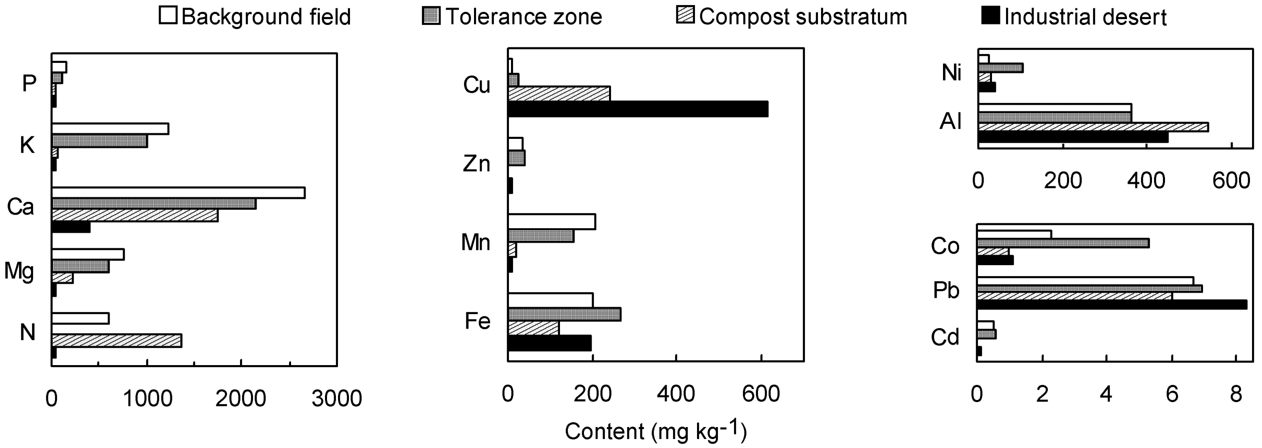
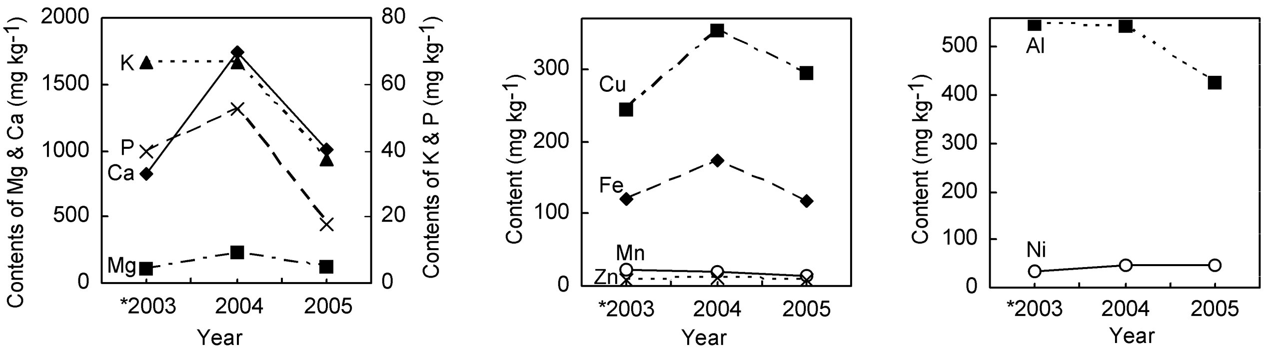


Figure 4. Comparison of soil elements by observation field in 2003; no data about total N (abbreviated as N) in the tolerance zone.

Soil transformation

There is a connection between the sampling conditions and the climatic conditions in the field. Temperature is the most important predictor of soil decomposition in the Arctic ecosystem (Heal et al. 1981); microbial respiration for biodegrading soil organic matter increases with temperature between 5°C and circa 25°C (Nadelhoffer et al. 1992). According to the climatic record for 2002 in Monchegorsk, monthly mean soil temperatures showed the following pattern: -13.5°C in January, -13.8°C in February, -11.5°C in March, -4.5°C in April, 7.5°C in May, 15.4°C in June, 18.8°C in July, 13.4°C in August, 6.8°C in September, -2.9°C in October, -14.9°C in November and -17.2°C in December. Therefore, not only phytoremediation but also soil transformation changed the soil properties. It is reasonable to interpret that the 2003 data on the compost substratum represent its primary properties, the 2004 data mainly represent abiogenic transformation, and the 2005 data represent abiogenic/biogenic transformation plus phytoremediation. Furthermore, it should be emphasized that the test field was subjected to metal pollution during the observation (see Table 1). It is necessary to consider this adverse effect on the artificial substratum. The analytical results in both 2003 and 2004 showed very small amounts of Co, Pb and Cd: 0.99 mg kg^{-1} Co, 6.05 mg kg^{-1} Pb and 0.06 mg kg^{-1} Cd in 2003; and 1.52 mg kg^{-1} Co, 6.44 mg kg^{-1} Pb and 0.14 mg kg^{-1} Cd in 2004. The other data of measured elements are classified into 3 types for convenience and are presented in Figure 5.

Metal contents in the soil showed a tendency to decrease in the rehabilitation test field in spite of the current pollution load during 2004 to 2005 (Figure 5). The Ca content clearly increased from 823 mg kg^{-1} in 2003 to 1,738 mg kg^{-1} in 2004 because Ca was transferred from co-composting materials (dolomite in particular) to the substratum and became bio-available; and the Mg content (224 mg kg^{-1}) doubled in 2004 (compare 105 mg kg^{-1} in 2003) and the reason seems to be the same as that for Ca (e.g. originating in the co-composting materials).



* primary property: compost substratum + plantation

Figure 5. Change of soil elements contained in the rehabilitation test field during 2003-2005.

The pH value slightly changed: 6.0 in 2003, 6.4 in 2004 and 5.4 in 2005. Although there is a statistical difference (p value < 0.001) in pH value between 2004 and 2005, these values are almost within the pH range where most nutrients are available for plant uptake (soil pH of 5.5 to 6.5 based on Bellows (2001)).

Leaf diagnosis

As stated in the section on site characteristics, the existing plants such as willow and birch have withstood metal pollution in the tolerance zone. Attention should be paid to excessive amounts of elements rather than deficiencies because micro-elements are required in very small amounts (e.g. a few mg kg^{-1}) in plant tissue, being one or more orders of magnitude lower than for essential elements (FFTC 2001). Table 2 shows that willow and birch leaves in the test field contained much greater amounts of metals than those in the background field – the amounts of Cu and Ni over 2003-2005 in particular. That is to say, these plants can survive even if the test field is suffering from metal pollution.

During 2004 to 2005, metal contents (Mg, Fe, Zn, Ni, Cu, Pb and Co) statistically (p value < 0.05) increased in willow leaves while their contents in birch leaves were rather stable. For essential elements, the safety margin beyond which plants are deemed to be consuming the elements in excess is fairly big, but for non-essential elements, the margin is generally very narrow: therefore, heavy metal availability sometimes induces ion stress. However, certain plants – known as metal hyperaccumulators – have the ability to extract elements from the soil and concentrate them in plant stems, shoots and leaves (ARS 2000). According to the Table 2, willow leaves in the test field contained 457.2 mg kg^{-1} Ni and 338.3 mg kg^{-1} Cu in 2005; by contrast those in the background field contained 2-3 mg kg^{-1} Ni and Cu in 2003.

DISCUSSION

The amounts of trace metals (Co, Pb and Cd) in the test field were smaller than those in the background field and the tolerance zone (Figure 4). As the compost substratum was not mixed with the soil originally located in the rehabilitation field, it is difficult to expect the substratum to have a reduction effect on these metals (i.e. dilution and metal affinity to compost material). It is reasonable that the background field and the tolerance zone originally contained greater amounts of these trace metals than the rehabilitation field, and these amounts have not damaged the local vegetation. As seen in the Figure 4 (soil analysis), the Cu content of 613 mg kg^{-1} in the industrial desert was over 190 times greater than that in the background field and about 24 times greater than that in the tolerance zone (Figure 4). Cu is generally accumulated in plant roots, and an excess amount of Cu damages the root system (Chino and Obata 1988); so it can be concluded that the deforestation resulted from an increase of heavy metal pollution (and/or unbalanced nutritional elements). The long-term pollution load (over several decades) must have changed the concentrations of soil elements contained in the land, and this suffering may continue in the future. However, metal availability in the test field considerably decreased during the observation (Figure 5). Leaf diagnosis based on elemental analysis shows a favorable trend (i.e. good performance of phytostabilization, Table 2) in the rehabilitation test, and this diagnosis indicates the possibility

Table 2. Elements contained in leaves of birch and willow sampled in the background field (2003) and in the rehabilitation field (2003-2005): background field is abbreviated as BG.

Element (mg kg^{-1})	Willow leaf				Birch leaf			
	BG	Rehabilitation field			BG	Rehabilitation field		
	2003	2003	2004	2005	2003	2003	2004	2005
P	2856.4	1680.2	2133.8	1909.2	2467.7	2481.7	2301.0	1858.3
K	7635.2	10370.9	7458.6	9030.2	6215.2	7348.0	7671.9	7082.0
Ca	10726.6	11965.7	14126.8	17235.6	8549.3	7807.0	9595.0	8569.7
Mg	2034.3	4154.4	4713.3	3628.8	2465.2	4507.0	3323.8	3416.2
Cu	2.3	18.9	590.7	338.3	5.0	18.5	254.1	209.4
Zn	161.3	238.3	121.4	180.4	180.5	126.0	176.6	144.6
Mn	845.3	1263.8	165.7	172.9	2555.9	1330.2	467.8	918.1
Fe	53.7	136.8	325.3	230.0	70.5	122.6	148.2	177.9
Ni	3.9	51.5	810.9	457.2	4.5	47.7	316.9	267.4
Al	44.2	69.1	219.0	169.7	29.8	60.3	84.9	106.8
Co	2.3	2.2	23.1	14.8	0.7	1.5	8.7	8.7
Pb	0.1	0.2	10.2	4.4	0.2	0.5	5.9	3.8
Cd	0.5	1.7	1.4	1.5	0.2	0.2	0.5	0.2

of phytoremediation (i.e. by willow and birch) in harsh Arctic (or Subarctic) regions. The contribution of phytoremediation to recovery of the polluted land is discussed below.

Metal pathways in plants

The data shown in Table 2 suggest that Ni, Cu and other metals can be removed from metal-contaminated land by harvesting the plants. However, more detailed research is necessary to assess whether metal superaccumulation has really taken place in the test field because there are basically two types of metal loading: (i) metals merely adhered to leaf surfaces (deposition of metal particles) and (ii) metals contained within plant tissues through air-foliar pathways and soil-root pathways (metal absorption). To put it differently, it is important to determine correctly a plant's concentration of each metal group – types (i) and (ii) – in order to evaluate the degree of metal accumulation in willow and birch. According to a birch experiment concerning smelter Cu and Ni depositions (Kozlov et al. 2000), the majority (80-95%) of Ni and Cu found in birch foliage in the heavily contaminated site is due to deposition of dust particles on leaf surfaces. ~35% of foliar Ni and ~15% of foliar Cu are in water soluble forms; washing of fresh leaves removes only a minor part of surface contaminants. It is therefore considered that Table 2 mainly represents type (ii) – metals stored within plant leaves through air-foliar pathways and soil-root pathways.

Metal distribution in plants

Only metals contained in leaves were measured in this test. Important question is how the absorbed metals are distributed within the plant. In case that the metals enter the plant's vascular system and then are ultimately deposited in leaf cells, the accumulated metals could be transferred to leaf-eating insects. The result is that the applied phytoremediation may change the local ecosystem; it is therefore important to understand metal behaviour within the plant. An uptake experiment of metals by birch (pot test) was conducted in the zone of the Monchegorsk smelter complexes (Kozlov et al. 2000). In this research the Ni and Cu were distributed to the leaves, stem and roots of the plant. Seedlings at the contaminated site suggest that both metals were transported from roots to stem and leaves, and the interaction between soil contamination and the exposure to air pollution resulted in enhancement of metal mobility. In conclusion, it is necessary to harvest a phytoremediator periodically in order to keep the damage to the local ecosystem to a minimum.

Type of phytoremediator

A phytoremediator has the ability to extract metal elements from the soil and concentrate them in the easily harvested plant stems, shoots, and leaves (LPS 2005). For instance, eucalyptus grows very fast, but it has a poor tolerance to the cold and is disease prone (Kovalick and Olexsey 1996). Willow and birch were tested in the observation field. The genus *Salix* is a member of the Salicaceae plant family. There are 400 species of willow, with more than 200 listed hybrids (Newsholme 1992). One of the characteristics of willow, which makes it a very suitable tree for use in phytoremediation, is that it can be frequently harvested by coppicing (Riddell-Black 1994). Two possible strategies have been proposed for the use of willow for phytoremediation (Punshon et al. 1996): (i) willows that survive in contaminated soil with minimal uptake of metals into the aerial tissues would be most appropriate for use where distribution of heavy metals to the wider environment or transfer of metals into the food chain is to be avoided; and (ii) willows that accumulate relatively high amounts of metal are desirable if soil remediation is to be achieved by phytoextraction and tree harvesting.

Phytoremediation makes it possible to remove metals from soil and concentrate them in plant tissues. This technology temporarily stores the removed metals in plant tissues; so the metals stay in the polluted site till the plant is harvested and translocated. Without harvesting and translocation, there is a possibility that the metals accumulated in the plant may be returned to the soil by litterfall and the demise of the plant. Possible end-product uses of phytoremediator biomass include fuel for direct burning as wood chips, raw material for the production of paper, particle board (also called "chipboard") and charcoal, the production of briquettes, ruminant livestock feed supplement and so on [see McElroy and Dawson (1986)]. However, the abovementioned uses are questionable from the viewpoint of risk assessment: (i) whether or not metals contained in biomass are vaporized and discharged to the atmosphere by burning; (ii) in phytoremediator combustion, whether metals contained in bottom ash and fly ash do not exceed the limit values for ash utilization; (iii) whether there is no problem in utilization of paper made from biomass containing metals (e.g. cigarette paper, paper packaging for food, etc.); (iv) whether it is safe to supply metal-containing food to livestock, and (v) whether metal-eating livestock have no adverse effect on human health through the food chain. Use of pytoremediators as biomass fuel is probably preferable in order to keep the environmental risk to a minimum if proper treatments of ash and flue gas are available. It seems to be easy to link a phytoremediator fuel with a renewable energy strategy. European bioenergy networks predict that bioenergy will be a main energy source beside the renewable ones like wind, hydropower, solar and geothermal energy (Lack 2002).

CONCLUSIONS

The Arctic is characterized by a harsh climate and poor-nutrient soil. Metal pollution currently imposed upon certain areas of test fields make the conditions even harsher. The combination of tolerant plants (birch and willow) with a compost substratum was used for a preliminary test (4 ha) in order to study how phytostabilization would work in metal-contaminated forest land affected by such conditions. The results obtained from chemical analysis of leaf elements (Table 2) showed a good efficiency of phytostabilization. For instance, Ni concentration and Cu concentration in the willow leaves in the test field were 208 times (2004) and 257 times (2004) greater, respectively, than those (2003) in the background field. What is more, the phytoremediators (birches and willows) have not withered since their plantation, that is, they can survive under such adverse conditions.

Biological remediation is recognized as a cost-effective measure, and the obtained data suggest that the phytoremediation technique (i.e. phytostabilization) is feasible even under severe conditions (harsh climate and serious metal contamination). However, there are still questions that need a fundamental research: clean-up efficiency (i.e. bio-available content vs. total content), effects of phytoremediator plants on the wider environment, and fate or disposal of high-metal biomass.

ACKNOWLEDGMENTS

This research project is organized by the Institute of the North Industrial Ecology Problem (Russian Academy of Science), and funding has been provided by RFFI grant No. 03 04 48628. Romeu Gerardo assisted a part of this work as his MSc study. The authors are grateful to anonymous referees for valuable comments and Ms C. Lentfer for English review.

REFERENCES

Agriculture Research Service (ARS). 2000. Phytoremediation using plant to clean up soils. Agricultural Research Magazine 48: 4-9.

Baklanov, A. 1994. Problems of air borne pollution at the Kola Peninsula. The European Association for the Science of Air Pollution (EURASAP) Newsletter 23: 5-11.

Balesdent, J., C. Chenu, M. Balabane. 2000. Relationship of soil organic matter dynamic to physical protection and tillage. Soil Tillage Research 52: 215– 230.

Bellows, B. 2001. Nutrient cycling in pastures. 63 p. National Center for Appropriate Technology. Fayetteville (AR).

Bridges, E.M. 1997. World Soils (3rd ed.). 179 p. Cambridge University Press, Cambridge.

Chino, M., H. Obata. 1988. Heavy metals and plants. In: Heavy Metals and Life (ed. M. Chino, H. Saito), pp. 81-143. Hakuyusha Co., Ltd., Tokyo.

Etana, A., I. Hakansson, E. Swain, S. Bucas. 1999. Effects of tillage depth on organic coal content and physical properties in five Swedish soils. Soil Tillage Research 52: 129–139.

Food and Fertilizer Technology Center (FFTC). 2001. Micronutrients and crop production. Report No. bc 51009. Taiwan: Food and Fertilizer Technology Center, Taipei.

Hamon, R.E., P.E. Holm, S.E. Lorenz, S.P. McGrath, T.H. Christensen. 1999. Metal uptake by plants from sludge-amended soil. Plant and Soil 216: 35-64.

Halonen O., H. Tulkki, J. Derome. 1983. Nutrient analysis methods. Metsantutkimuslaitoksen tiedonantoja 121: 1-28.

Heal, O.W., P.W. Flanagan, D.D. French, S. MacLean. 1981. Decomposition and accumulation of organic matter in tundra. In: Tundra Ecosystems – a Comparative Analysis (ed. L.Bliss, O. Hewal, J. Moore), pp. 587-633. Cambridge University Press, Cambridge.

Koptsik, S.V., G.N. Koptsik. 2001. Soil pollution patterns in terrestrial ecosystems of the Kola Peninsula. In: Sustaining the global farm (ed. D. Stott, R. Mohtar, G. Steinhardt). pp 212-216. Purdue University Press, Purdue (ID).

Kovalick, W.W., R. Olexsey (eds.). 1996. Workshop on Phytoremediation of Organic Wastes, Meeting Summary, U.S. Environmental Protection Agency, December 17-19, Fort. Worth (TX).

Kozlov, M.V., E. Haukioja, A.V. Bakhtiarov, D.N. Stroganov, S.N. Zimina. 2000. Root versus canopy uptake of heavy metals by birch in an industrially polluted area: contrasting behaviour of nickel and copper. Environmental Pollution 107: 413-420.

Lack, N. 2002. EUBIONET – biomass survey in Europe. 14 p. European Bioenergy Networks, Gulzow.

Leucaena Production Society (LPS). 2005. Fitoremediation Plant Spectrum. Report No. ENVIROH-2, Honduras: Creating Consortiums for Export Training and EcoBusiness Development, Intibuca.

Lukina, N., V. Nikonov. 1996. Biogeochemical cycle in the northern forest subjected to air pollution. 65 p. Kola Science Center, Apatity (in Russian).

Mäkinen, A. 1994. Biomonitoring of atmospheric deposition in the Kola Peninsula and Finnish Lapland based on the chemical analysis of mosses. Report No. 4. Environmental Policy Department – Ministry of Environment, Helsinki.

McElroy, G.H., W.M. Dawson. 1986. Biomass from short-rotation coppice willow on marginal land. Biomass 10: 225–240.

Nadelhoffer, K.J., A.E. Giblin, G.R. Shaver, A.E. Linkins. 1992. Microbial processes and plant nutrient availability in arctic soils. In: Arctic Ecosystem in a Changing Climate (ed. F. Chapin, R. Jefferies, J. Reynolds, G. Shaver, J. Svoboda, E. Chu), pp. 281-300. Academic Press, San Diego (CA).

Newsholme, C. 1992. Willows: the genus *Salix*. 224 p. Batsford Ltd., London.

Nilsson, A. 1997. Arctic pollution issues – a state of the Arctic environment report. No. 82-7655-060-6. Arctic Monitoring & Assessment Program, Oslo.

Orlov, D.S. 1992. Soil Chemistry. 34 p. Moscow State University Press, Moscow.

Riddell-Black, D. 1994. Heavy metal uptake by fast growing willow species. In: Willow Vegetation Filters for Municipal Wastewaters and Sludges – a Biological Purification System (ed. P. Aronsson, K. Perttu), pp 145-151. Swedish University of Agricultural Sciences, Uppsala.

Pulford, I., C. Watson. 2003. Phytoremediation of heavy metal-contaminated land by trees – a review. Environmental International 29: 529-540.

Punshon T., N.M Dickinson, N.W. Lepp. 1996. The potential of *Salix* clones for bioremediating metal polluted soil. In: Heavy Metals and Trees (ed. I. Glimmerveen), pp. 93–104. Institute of Chartered Foresters, Edinburgh.

United Nations Environment Program (UNEP). 2001. Significant changes likely in the Arctic from climate changes. UNEP News Release 01/26. Kenya: UNEP Media Office, Nairobi.

Semple, K.T., B.J. Reid, T.R. Fermor. 2001. Impact of composting strategies on the treatment of soil contaminated with organic pollutants. Environmental Pollution 112: 269-283.

Witting, R., H. Neite. 1989. Distribution of lead in the soils of *Fagus sylvatica* forest in Europe. In: Plant and Pollutants in Developed and Developing Countries (ed. M.A. Oztur), pp. 199-206. Turkey: Ege University Press, Izmir.

Woodmansee, R., G. I. Vallis, J.J. Mott. 1981. Grassland Nitrogen. In: Terrestrial Nitrogen Cycles: Processes, Ecosystem Strategies and Management Impacts, Ecological Bulletins 33 (ed. F. Clark, T. Rosswall), pp. 443-462. Sweden: Swedish Natural Science Research Council, Stockholm.