Current state of terrestrial ecosystems in the joint Norwegian, Russian and Finnish border area

Project Ka 00 72 Interreg III Kolarctic/ Final report
Development and implementation of an environmental monitoring and assessment programme in the joint Finnish, Norwegian and Russian border area, 2003 - 2006

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INEP ФГУ ВСЕРОССИЙСКИЙ НАУЧНО-ИССЛЕДОВАТЕЛЬСКИЙ ИНСТИТУТ ОХРАНЫ ПРИРОДЫ ФГУ «ВНИИприроды» ИГКЭ IGCE

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1. Introduction

From the late 1980's onwards, the effects of emissions from the Pechenganikel and the Zapolyarnij smelters on terrestrial ecosystems in the NW part of the Kola Peninsula and in adjoining parts of Norway and Finland have been monitored and studied in a number of national and international projects (e.g. Finnish Lapland Forest Damage Project, the Skogforsk-NINA-VNIIPRIRODA-IGCE Project, the NINA-NGU-INEP-METLA Project). The results of these projects have clearly shown that the terrestrial ecosystems in the immediate surroundings of the smelters are severely damaged or even completely destroyed, and that the ecosystems located at greater distances from the smelters are suffering from both visible and non-visible damage.

Trees, vascular plants, mosses and lichens are all affected. Visible injuries to vegetation caused by SO_2 are common, and symptoms are visible on a number of species, including Scots pine (*Pinus sylvestris*), downy birch (*Betula pubescens*), bilberry (*Vaccinium myrtillus*) and dwarf birch (*Betula nana*) (Aamlid 1993). In the immediate vicinity of the smelters the forests are dead or severely damaged (Vassilieva 1992, 1993). The coverage of epiphytic lichens has been drastically reduced (Aamlid and Skogheim 2001), and critical levels of heavy metals are exceeded over more than 3,200 km^2 of the border area (SFT 2002). The coverage of epigeic lichens (reindeer lichens, e.g. *Cladonia arbuscula* and *C. stellaris*) decreased significantly in the area during the period 1973-1999 (Tømmervik et al. 1998, 2003). The functioning of the more sensitive components of the ecosystems is thus seriously disturbed in many parts of the region (Tikkanen and Niemelä 1995, Reimann et al. 1998, SFT 2002). The photosynthetic efficiency of needles/leaves of Scots pine (*Pinus sylvestris*) and birch (*Betula pubescens*) has also decreased along the Russian-Norwegian border due to the effects of air pollutants (Odasz-Albrigtsen et al. 2001). Non-visible symptoms of damage to the cellular tissue in Scots pine needles have been recorded at distances of over 100 km to the west of the smelter (Tikkanen and Niemelä 1995). The vegetation and soil layers are contaminated with heavy metals, and there are clear signs of decreased soil fertility and increased soil acidity probably also affecting the species composition of the ground vegetation (Lukina and Nikonov 1997, Derome et al. 1998, Aamlid et al. 2000, Steinnes et al. 2000). Long-term monitoring of lakes and rivers has also revealed substantial surface water acidification (Traaen et al. 1991). The accumulation of heavy metals has also been reported in small vertebrates, particularly in the vicinity of the smelters (Kålås et al. 1993, Henttonen et al. 2002). Accumulation occurred in the liver of small mammals, particularly in species of the second trophic level e.g. the common shrew (*Sorex araneus*), which feeds on invertebrates living in the soil.

The Nordic Investment Bank and the Norwegian government are supporting the modernisation of the smelter in Nikel. The goal is to reduce the emissions by 90%, and thereby decrease the pollution impact in the region. The sub-project is a synthesis of elements of several previous cross-border projects in the region with the aim of collecting reference data on the state of the terrestrial ecosystem before the modernisation of the smelter. This is of crucial importance for monitoring the future recovery of the environmental condition after emissions have been reduced.

The aim of this part (terrestrial ecosystem sub-project) of the project was to develop and implement a monitoring and assessment programme for terrestrial ecosystems in the joint Finnish, Norwegian and Russian border area. The sub-project was carried out in six stages:

1) Evaluation of the sufficiency of existing monitoring activities.
2) Harmonization of the monitoring and assessment methods (sampling, measurement and observation, laboratory analyses, data analysis, evaluation and reporting) required for monitoring terrestrial ecosystems.
3) Development of methods for assessing new parameters depicting terrestrial ecosystem condition and functioning in the region.

4) Testing of the integrated monitoring programme, to be implemented by the environmental authorities and organizations of the three countries, during the period when emissions from the Pechenganikel smelter complex are expected to decrease as a result of renovation of the smelter.
5) Assessment of the state of terrestrial ecosystems in the region.
6) Compilation of recommendations for a future joint monitoring programme.

2. Establishment of an environmental monitoring network in the joint Finnish, Norwegian and Russian border area, and evaluation of the sufficiency of existing monitoring activities

Background and aims

The primary objectives are to integrate and harmonise the monitoring activities that have already been carried out by Norway, Russia and Finland on the effects of emissions from the Pechenganikel smelter on terrestrial ecosystems in the border area, and to identify relatively sensitive and cost effective parameters for future monitoring activities in the area. In order to fulfil these objectives a terrestrial ecosystem monitoring network (ECM) has been established in Norway, Russia and Finland based on existing monitoring networks. Dormant intensive monitoring plots have been activated, and the measurements and assessments required to up-date the baseline information were carried out in 2004 and 2005.

Establishment of the ecosystem monitoring network (ECM)

The new ecosystem monitoring network (ECM) consists of selected plots from three earlier established forest monitoring networks (Fig. 1):

1. The Finnish Lapland Forest Damage Project monitoring network, established in 1990-1995
2. The Skogforsk-NINA-VNIIPRIRODA-IGCE monitoring network with eight plots along a transect from the Nikel smelter towards Norway, established in 1994-1998 (Aamlid et al. 2000)
3. The NINA-NGU-INEP-METLA monitoring network with 31 plots along a north-south and a west-east transect running through the Nikel area, established in 2000-2001 (Yoccoz et al. 2001)

In addition to the above plots, studies on bird and small mammals have been carried out along transects running westwards from the River Pas, and these transects were incorporated in the new ecosystem monitoring network. The bird transect had been sampled in 2000, and two different transects for micro-mammalia (rodents *Microtidae* and shrew *Soricidae*) sampled during the period 1985 - 2004. These projects were carried out by the Svanhovd Environmental Centre and Pasvik Zapovednik.

The existing monitoring network included activities on a wide range of terrestrial parameters covering tree crown condition, tree (stand) growth, species composition of ground vegetation, epiphytic lichens on birch and pine stems, plant vitality measured on the basis of photosynthetic efficiency, chemical analyses of mosses, lichens and vascular plants, species composition of hole-nesting passerines (birds) and small mammals (rodents and shrew), chemical properties of the organic and uppermost mineral soil layers, and the chemical composition of bulk deposition and stand throughfall. These networks had a different plot and sampling design (see Section 4.1), primarily because they were originally designed to monitor some different components of forest ecosystems. As the distribution of the plots overlapped to some extent, it was considered unnecessary to include all the established plots in the new network.

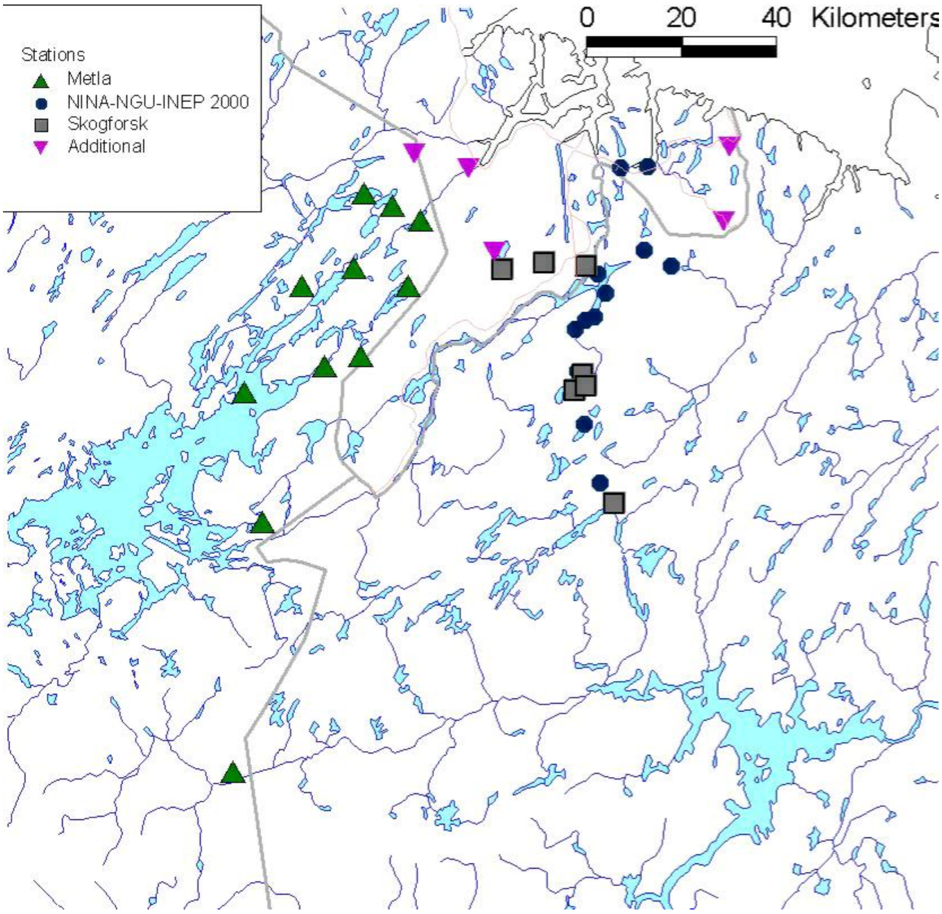

Figure 2.1 Terrestrial monitoring plots established within the area affected by emissions from the Nikel and Zapolyjarni smelters, as well as in adjacent areas, in three separate monitoring programmes during 1990–2004.

The new ecosystem monitoring network was established in forested areas (pine and birch forests), and tested in 2004 and 2005 with a total of 23 plots: 10 in Russia, 5 in Norway and 11 in Finland (Fig. 2.2). The plots represent a north-south and an east-west gradient related to the emission point sources at the Nikel and the Zapolyarnij smelters, and includes both heavily affected areas and undisturbed reference plots. However, the selection of number of plots, as well as the parameters to be measured on the plots, was also based on a cost-benefit evaluation.

Plots PA, PB, PC and PD (in Norway) and RUS0, RUS1 and RUS3 (in Russia) were selected from the Skogforsk-NINA-VNIIPRIRODA-IGCE network. Plots S3, S5, S10, N6 (in Russia) and N11 (in Norway) were selected from the NINA-NGU-INEP-METLA network. Plots F1 – F11 were selected from the Finnish Lapland Forest Damage Project. An additional plot was established for bird studies close to Jeniskoski in Russia (80 km SSW of Nikel) in order to compare species composition and nesting dates.

We selected, on the basis of the results obtained earlier with the different networks, a list of parameters (Table 2.1) that should be measured on the new ecosystem monitoring network. Bulk deposition and stand throughfall were to be monitored continually over a period of one year (total of 8 plots; 3 in Russia, 2 in Norway, 3 in Finland). Assessment of tree condition and growth, ground vegetation, epiphytic lichens, metal concentrations in certain plants and the litter and organic layers were carried out on all the plots during one summer, while studies on photosynthetic efficiency, birds and mammals were carried out on a limited number of plots.

Five sites were selected as a minimum number of plots for monitoring bulk deposition and stand throughfall in order to obtain reliable information about the deposition of pollutants within the monitoring area. The plots were located on transects running to the north, south and west of the Nikel smelter (Fig. 2.2). Two additional plots in Finland were selected as background sites (F-10 and F-11).

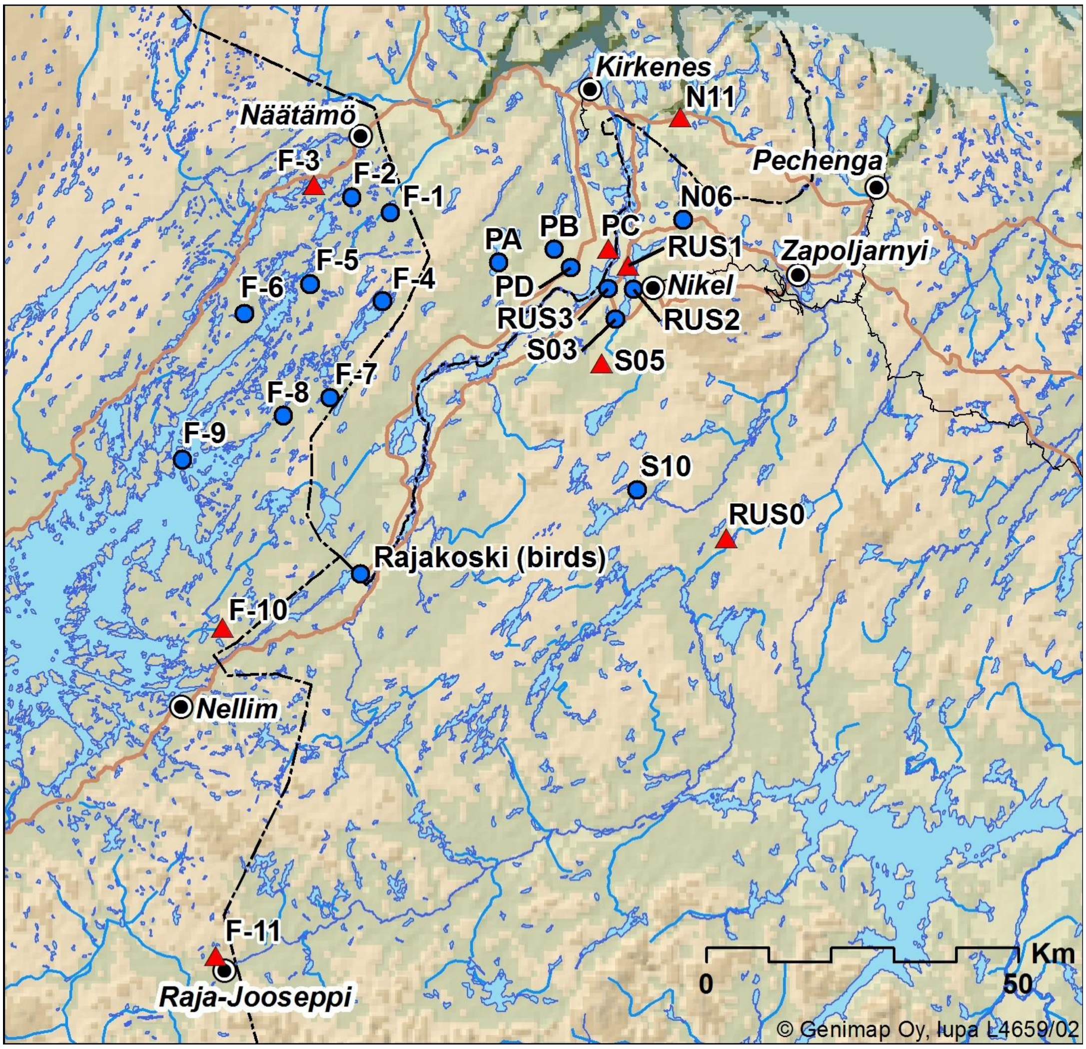

Figure 2.2 Location of the Ecosystem Monitoring Network (ECM) plots in Russia, Finland and Norway monitored during 2004-2005.

Table 2.1 The plots selected for testing the terrestrial ecosystem monitoring network in Russia, Norway and Finland and the parameters monitored on the plots during 2004-2005. The assessment of birds and small mammals (*) was carried out in the vicinity of the plots.

Country	**Plot**	**Wet deposition**	**Crown condition**	**Stand growth**	**Ground vegetation**	**Epiphytic lichens**	**Photo-synthesis**	**Plant chemistry**	**Birds**	**Small mammals**	**Soil**
Russia	RUS0	X	X	X	X	X		X			X
	RUS1	X	X	X	X	X		X			X
	RUS2		X	X	X	X		X	X		X
	RUS3								X		X
	S03		X		X	X	X	X			X
	S05	X	X		X	X	X	X			X
	S10		X		X	X	X	X			X
	N6		X		X	X	X	X			X
	Rajakoski								X		
Norway	N11	X	X		X	X	X	X			X
	PA		X	X	X	X		X	X*		X
	PB	X	X	X	X	X		X	X*	X*	X
	PC		X	X	X	X		X	X*		X
	PD		X	X	X	X		X	X*	X*	X
Finland	F-1		X	X	X	X		X			X
	F-2		X	X	X	X		X			X
	F-3	X	X	X	X	X		X			X
	F-4		X	X	X	X		X			X
	F-5		X	X	X	X		X			X
	F-6		X	X	X	X		X			X
	F-7		X	X	X	X		X			X
	F-8		X	X	X	X		X			X
	F-9		X	X	X	X		X			X
	F-10	X									
	F-11	X									

3. Harmonization of the environmental monitoring and assessment methods employed in the sampling, measurement/observation, data analysis, evaluation and reporting stages

Harmonization was achieved by carrying out joint sampling and assessment exercises at selected sites, inter-laboratory ring tests for the chemical analyses of deposition, plant and soil material, and by drawing up data compilation, data analysis and reporting guidelines and templates for the researchers working in the three countries.

Joint sampling and assessment exercises in the field

Joint sampling and assessment exercises were carried out at sites in Norway and in Russia during establishment of the new ecosystem monitoring network. In addition, a common sampling and assessment course was held at the Rayakoski workshop (2.-3.8.2004) in Russia before the start of the field work, with participating researchers from Norway, Russia and Finland. Determination of critical taxa of bryophytes and lichens and methods of assessing species abundance, crown conditions, stand growth and epiphytic lichens was emphasized.

Inter-laboratory ring tests

The laboratories responsible for analysing the deposition, plant and soil samples in the sub-project were the laboratory of the Norwegian Forest and Landscape Institute (formerly the Norwegian Forest Research Institute, Skogforsk) in Norway, the terrestrial ecosystems laboratory of the Institute of the Industrial Ecology of the North (Kola Science Centre, Russian Academy of Sciences, INEP KSC RAS) in Russia, and the laboratory of the Rovaniemi Research Unit of the Finnish Forest Research Institute (Metla).

Deposition analyses

The three laboratories participated in WRT2005 (Marchetto et al. 2006), which was an inter-laboratory ring test for deposition and soil solution samples organized with co-funding from the EU Forest Focus forest monitoring programme, and supervised by the ICP Forests Expert Panel on Deposition. 58 laboratories from most European countries participated in WRT 2005 in May 2005. Five natural deposition samples (bulk deposition and stand throughfall) and 4 synthetic samples were sent to each laboratory for analysis. The analyses performed were pH, alkalinity, dissolved organic carbon (DOC), NH_4, NO_3, total N, SO_4, Cl, PO_4, Ca, Mg, K, Na, Al, Cd, Co, Cu, Mn, Ni, Pb, and Zn. The total number of individual analyses performed on the samples was over 250. The three laboratories performed satisfactorily in the ring test (Fig. 3.1): for Norway 95% of the results were within the acceptable range for the individual analyses, for Finland 84% and for Russia 81%. However, the results that were outside the acceptable range (Norway 5%, Finland 16%, Russia 19%) were within 5% of the acceptable range.

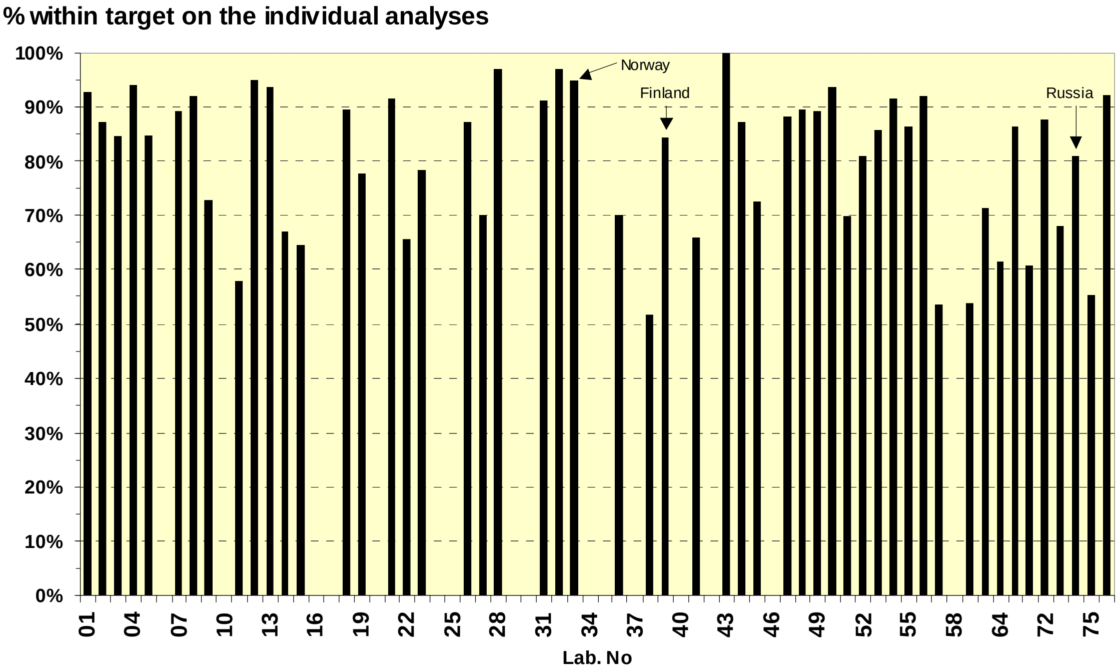

Figure. 3.1 Results of an inter-laboratory ring test (WRT 2005) carried out in May 2005 for deposition and soil solution samples organized with co-funding from the EU Forest Focus forest monitoring programme, and supervised by the ICP Forests Expert Panel on Deposiiton. The Norwegian, Finnish and Russian laboratories participating in the project are marked on the figure.

Plant and humus analyses

The three laboratories also participated in an inter-laboratory ring test arranged as a part of the activities of the sub-project. Samples of the organic layer, bilberry (Vaccinium myrtillus) leaves, pine (Pinus sylvestris) and birch (Betula spp.) leaves were taken during the joint sampling and assessment exercise in the field, carried out at Rayakoski in Russia on
2.–3.8.2004. The site is known to have relatively elevated heavy metal and total sulphur concentrations in the soil and plant samples, and therefore they were considered representative of the actual field samples collected as a part of the monitoring programme of the sub-project elsewhere in the area. The samples were taken to the laboratory of the Rovaniemi Research Unit (Metla), dried, milled and homogenised. Samples were sent to the three laboratories for analysis of total metals and total S, P, N and C on the plant and humus samples, and pH, exchangeable acidity, cation exchange capacity, base cations, and exchangeable metals on the organic layer sample. All three laboratories used microwave digestion for determining total concentrations in the plant samples, but the individual laboratories used slightly different digestion mixtures (Table 3.1). The laboratories also used different extractant solutions for determining exchangeable cations (Table 3.2).

The results for the total analyses on the plant and humus samples by the individual laboratories were relatively compatible, especially in the case of heavy metals such as Cu, Ni, Pb and Zn, which are the major pollutants derived from the smelters and hence important for the monitoring programme (Table 3.1). The differences between the Cr and Cd concentrations were relatively large but, as these metals were present at very low concentrations, the variation is acceptable. Part of the differences are undoubtedly due to differences between the digestion mixtures used by the individual laboratories, and not to poor quality of the analytical work. The results obtained by the individual laboratories for pH, exchangeable

Table 3.1 Total concentrations of heavy metals, macronutrients (Ca, Mg, K) and total phosphorus, sulphur, carbon and nitrogen in reference birch leaves, pine needles, bilberry leaves and humus samples analysed by the Finnish, Norwegian and Russian laboratories in the inter-laboratory comparison exercise. The elements were determined by wet digestion (microwave oven). In Finland a mixture of nitric acid and hydrogen peroxide ($HNO_3 + H_2O_2$) was used as the digestion mixture, in Norway nitric acid and perchloric acid ($HNO_3 + HClO_3$), and in Russia nitric acid (HNO_3). <LOQ = below the Limit of Quantitation. na = not analysed owing to insufficient sample.

	Country	Al mg/kg	Ca mg/kg	Cd mg/kg	Cr mg/kg	Cu mg/kg	Fe mg/kg	K mg/kg	Mg mg/kg	Mn mg/kg	Ni mg/kg	P mg/kg	Pb mg/kg	S mg/kg	Zn mg/kg	Tot-C %	Tot-N %
Birch leaves	Finland	64	8455	<LOQ	1.1	7.8	123	11040	3662	1544	6.7	2405	<LOQ	1713	197	49.1	2.37
	Norway	74	10000	0.2	1.1	7.5	118	10400	4000	1528	5.7	2400	0.4	1600	200	na	na
	Russia	30	9450	0.1	0.9	8.7	132	11175	3259	1405	9.5	2495	0.6	1180	232	48.3	2.43
Pine needles	Finland	266	3332	<LOQ	0.5	3.8	38	4787	878	931	1.7	1342	<LOQ	959	53	51.9	1.31
	Norway	332	3600	0.2	1.1	2.7	39	4600	900	920	1.1	1400	0.4	900	56	51.7	1.12
	Russia	238	3636	0.1	0.3	3.4	42	5024	882	887	1.5	1420	1.2	616	50	56.4	1.21
Bil-berry leaves	Finland	145	6143	1.4	<LOQ	10.9	88	10086	2001	848	3.0	1342	<LOQ	1736	11	48.1	1.43
	Norway	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
	Russia	103	6047	0.3	0.2	9.5	82	9795	1655	762	2.5	1342	0.6	1368	11	51.8	1.44
Humus	Finland	5567	3324	0.1	137.2	22.5	8769	1442	2029	287	95.9	819	10.7	1007	49.5	30.6	0.82
	Norway	3135	2489	0.2	81.5	21.2	5998	1036	967	236	68.9	842	8.1	921	44.6	34.3	0.83
	Russia	3101	2013	0.1	158.6	18.3	7289	1297	1476	285	87.2	589	9.8	857	43.4	33.0	0.84

cations etc. of the reference humus sample (Table 3.2) were very variable, especially for the important base cations (Ca, Mg). The main reason for this is that the laboratories used different extraction solutions.

Data analysis, evaluation and reporting stages

One researcher was responsible for collating and checking, in co-operation with the other researchers, the datasets for each of the groups of monitoring parameters (see Sections 4.1- 4.11.). The data files for each group of parameters, as well as information about the sampling, chemical analyses etc., were incorporated in the database as both data files and metadata files. One researcher was responsible for preparing an evaluation and report, in co-operation with the other researchers, for each of the individual groups of monitoring parameters

Table. 3.2 pH and concentrations of exchangeable Al, Ca, Fe, K, Mg, Mn and Na and exchangeable acidity, cation exchange capacity (CEC) and base saturation (BS) in a reference humus samples analysed by the Finnish, Norwegian and Russian laboratories in the inter-laboratory comparison exercise. In Finland the samples was extracted with barium chloride ($BaCl_2$), in Norway with ammonium nitrate (NH_4NO_3), and in Russia with ammonium acetate (CH_3COONH_4).

	Country	pH H2O	pH CaCl2	Al mg/kg	Ca mg/kg	Fe mg/kg	K mg/kg	Mg mg/kg	Mn mg/kg	Na mg/kg	Exch Ac. meq/kg	CEC meq/kg	BS %
Humus	Finland	3.99	3.31	341	3111	504	727	600	197	42.0	130	355	63.4
	Norway	3.75	3.27	314	1834	390	794	511	210	39.1	87	232	59.0
	Russia	3.52	3.00	310	1248	127	748	242	205	36.0			

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4. Testing the integrated monitoring programme, to be implemented by the environmental authorities and organizations of the three countries, during the period when emissions from the Pechenganikel smelter complex are expected to decrease as a result of renovation of the smelter

4.1 General information about the monitoring plots

The ecosystem monitoring network (ECM) consists of plots from three earlier established monitoring networks, with different plot design.

The eight plots from the Skogforsk-NINA-VNIIPRIRODA-IGCE monitoring network (PA, PB, PC, PD, RUS0, RUS1, RUS2 and RUS3) were established in Scots pine and Norway spruce forests. They all have a rectangular design with a total area of 30 x 50 m (1500 m^2) (Fig. 4.1). An inner site area of 25 x 40 m (1000 m^2) was intended for non-destructive sampling with a minimum of disturbance, while the outer buffer zone was mainly established for destructive sampling (cf. Aamlid et al. 2000) .

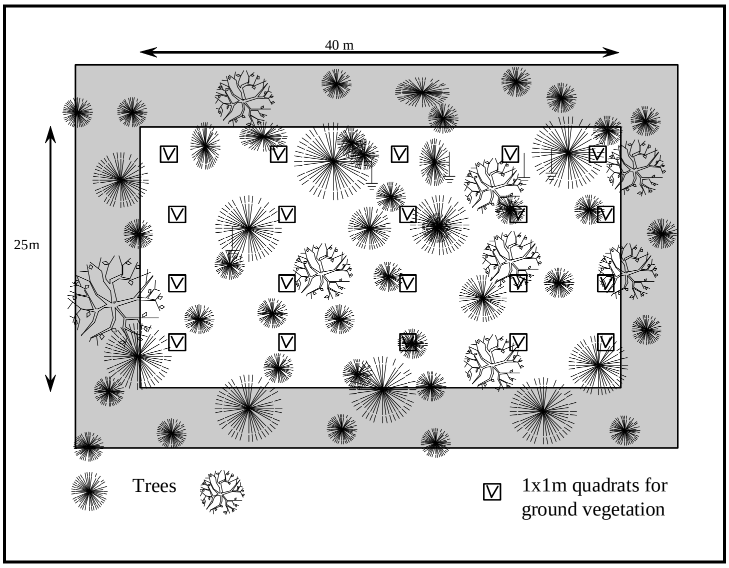


Figure 4.1 Design of the Skogforsk-NINA-VNIIPRIRODA-IGCE monitoring plots.

The five selected plots from the NINA-NGU-INEP-METLA monitoring network (S3, S5, S10, N6 and N11) were established in birch forests, and each consists of five sub-plots (A, B, C, D and E) for the assessment of terrestrial parameters (Fig. 4.2). Each-sub –plot is 15 x 15 m (225 m^2), and the total plot area is 1125 m^2. E is the central sub-plot, and the distance from the centre of E to the centre of each of the other sub-plots is 25 meters (cf. Yoccoz et al. 2001).

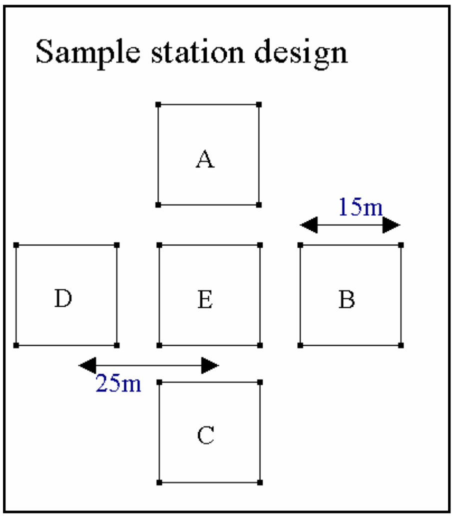
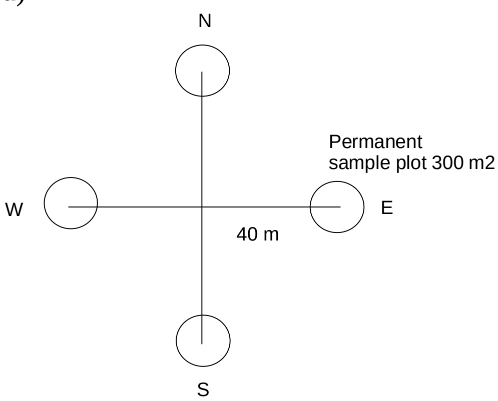


Figure 4.2. Design of the NINA-NGU-INEP-METLA plots.

The nine clusters selected from the Finnish Lapland Damage Project (F-1 to F-9) were all established in pine forests. Each cluster consists of 3 - 4 circular plots (Fig. 4.3a). One plot, which represented the ground vegetation of the whole cluster, was selected as a sample plot for the Pasvik project. The size of the plot is 300 m^2, with a radius of 9.8 m (Fig. 4.3b).

a)



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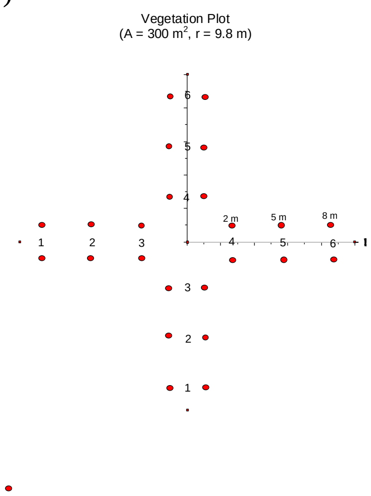

Figure 4.3 Design of a) the sample clusters, and b) vegetation plots used in the Lapland Forest Damage Project.

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4.2. Deposition

Bulk deposition and stand throughfall were monitored on a total of 8 plots in Norway, Russia and Finland for a period of one year during 2004-2005. The plot numbers in the individual countries and the sampling periods are given in Table 4.1. The equipment for collecting the rain and snow samples was the same on all the plots, and was based on the design used in Finland as a part of the Forest Focus/ICP Forest deposition monitoring programmes. Bulk deposition was monitored during the snowfree period using 5 rainfall collectors located in an open area (i.e. no tree cover) close to the plots, and 3 snowfall collectors located at the same points during the winter. Stand throughfall was collected during the snowfree period using 20 rainfall collectors located systematically in a circle inside the stand at a distance of 9.8 m from the centre point of the plot. The collectors were emptied at 4-week intervals. During the snowfree period all the samples from the bulk deposition and stand throughfall collectors were bulked on site to give one composite sample for each type of sample. The total volume of the bulked samples was recorded (determined by weighing, 1 g = 1 ml) in the field, and a sub-sample (1 l) was sent to the laboratory for analysis. During the winter the samples in all the individual collectors had to be transported to the laboratory for thawing, weighing and bulking. Maintenance of the collectors in the field, sampling and transport to the laboratory were carried out in accordance with the field manual of the Finnish version of the Forest Focus/ICP Forests deposition monitoring programme (ICP Forests, 2005).

Table 4.1 The plots used for monitoring bulk deposition and stand throughfall in Russia, Norway and Finland during 2004-2005.

Country	**Plot**	**Distance from the emission sources, km**	**Tree species**	**Sampling period**
Russia	RUS0	43	Birch	4.10.04-1.10.05
	RUS1	6	Scots pine	4.10.04-1.10.05
	S05	12	Birch	1.6.04-1.10.05
Norway	N11	30	Birch	1.6.04-8.6.05
	PB	14	Scots pine	1.6.04-8.6.05
Finland	F-3	58	Scots pine	1.6.04-13.6.05
	F-10	90	Scots pine	1.6.04-13.6.05
	F-11	131	Scots pine	1.6.04-13.6.05

The plots in Norway, Finland and one of the plots in Russia (S05) were established at the beginning of June, 2004. For logistical reasons the other two plots in Russia (RUS0 and RUS1) were established at the beginning of October, 2004. Sampling was carried out over a period of approximately one year. Because the sampling period was not exactly one year, the results for annual deposition were adjusted accordingly. The results for bulk deposition (open area collection) on plot S05 are not presented here owing to the fact that a high proportion of the collectors were destroyed by vandalism, and annual deposition values therefore could not be calculated.

The proximity of the sea, and the large variation in topography and the prevailing wind directions, produce relatively high local variation in the annual amount of precipitation. The long-term annual average precipitation for the area varies between 350 and 450 mm, with somewhat higher values close to the coast. The permanent snow cover usually lasts from mid-November to late May. A higher proportion of precipitation falls as snow on the Finnish plots as they are located at higher altitudes inland, and the winter is correspondingly longer. In 2004/5, the annual precipitation on the monitoring plots in Russia and Finland ranged between 420–500 mm, which was slightly higher than the long-term average (Table 4.2). On the two plots in Norway (N11 and PB), which are the closest to the sea, the annual precipitation was 680 and 720 mm.

Table 4.2 Distance from the emission source, and the annual precipitation (open area), average pH and deposition of metals, cations and anions in bulk deposition at the plots in Russia, Norway and Finland in 2004-2005. nd = no data available.

Plot	Distance, km	Precip. mm	pH	Cu mg/m^2	Ni mg/m^2	SO_4-S mg/m^2	Zn mg/m^2	Fe mg/m^2	Al mg/m^2
RUS1	6	461	4.62	20.9	17.3	102	4.0	14.0	6.3
PB	14	722	4.94	24.4	27.3	355	8.6	16.5	9.8
S05	17	nm	nd	nd	nd	nd	nd	nd	nd
N11	30	678	4.91	10.0	7.8	331	5.8	5.6	10.5
RUS0	43	423	4.51	1.5	0.9	53	4.8	3.7	5.7
F-3	58	485	4.95	1.7	2.7	103	6.2	1.0	7.3
F-10	90	444	4.96	1.0	2.2	105	6.5	1.5	6.7
F-11	131	500	4.83	1.0	2.5	94	6.1	1.0	8.4

Plot	Distance, km	Na mg/m^2	Cl mg/m^2	Ca mg/m^2	Mg mg/m^2	K mg/m^2	NO_3-N mg/m^2	NH_4-N mg/m^2
RUS1	6	414	898	70.7	73.2	73.7	7.1	51.3
PB	14	517	1686	74.3	104	73.7	57.0	60.5
S05	17	nd	nd	nd	nd	nd	nd	nd
N11	30	763	2188	86.8	123	66.9	61.6	52.7
RUS0	43	130	316	24.7	19.6	22.2	8.6	54.4
F-3	58	175	306	23.4	23.5	27.3	38.4	28.8
F-10	90	131	218	40.9	27.8	69.9	33.5	17.1
F-11	131	84	138	21.7	10.4	28.4	48.5	30.5

The bulk deposition of sulphate was relatively high at the two plots (331 and 355 mg SO_4-S/m^2/a) in Norway (Table 4.2), while on all the other plots sulphate deposition was low (53–105 mg SO_4-S/m^2/a) and similar to the deposition level at e.g. Pallasjärvi (average 102 mg SO_4-S/m^2/a during 2001-2004), which is considered to represent background deposition levels (Lindroos et al. 2007). There was no statistically significant relationship between the bulk deposition of sulphate on the plots and the distance to the emissions sources (Fig. 4.4). The plots received sulphate from two sources: the Pechenganikel smelters (gaseous SO_2 and SO_4^{2-}), and sulphate in aerosols from the sea (e.g. as $MgSO_4$). The SO_2 emitted by the Pechenganikel smelters reaches the plots within a relatively short period of time and, in the dry, cold climate, only small amounts of SO_2 will be oxidized to sulphate. Furthermore, during the cold, dark arctic winter there is no solar radiation to catalyze the photochemical oxidation processes of SO_2. The contribution of dry deposition to total (dry + wet) deposition is expected to be high in the Finnmark region due to the relatively high air concentrations and low precipitation. At Karasjok in Norway, the contribution of sulphur dry deposition to total deposition is estimated to be 53% in winter and 50% in summer. The lack of statistically significant correlation between sulphate and Cu and Ni deposition and between pH and sulphate deposition, and the significant correlation between sulphate and Mg, Na and Cl deposition (Table 4.4), strongly suggests that most of the sulphate is derived from marine sources, and not from the smelters.

There was a statistically significant correlation between annual Cu and Fe deposition and the distance to the smelters, and almost significant correlation for Ni (Fig. 4.4.). However, as the plots are located to the north, south and west of the emission sources, and the prevailing wind is from the S/SW, then it is clear that highly significant correlations between deposition levels and distance from the smelters cannot be expected. Despite this, it is clear that the deposition of heavy metals extends, in these directions, only to a distance of less than 50 km from the smelters. There is almost no information available about deposition levels to the E and NE of the smelters.

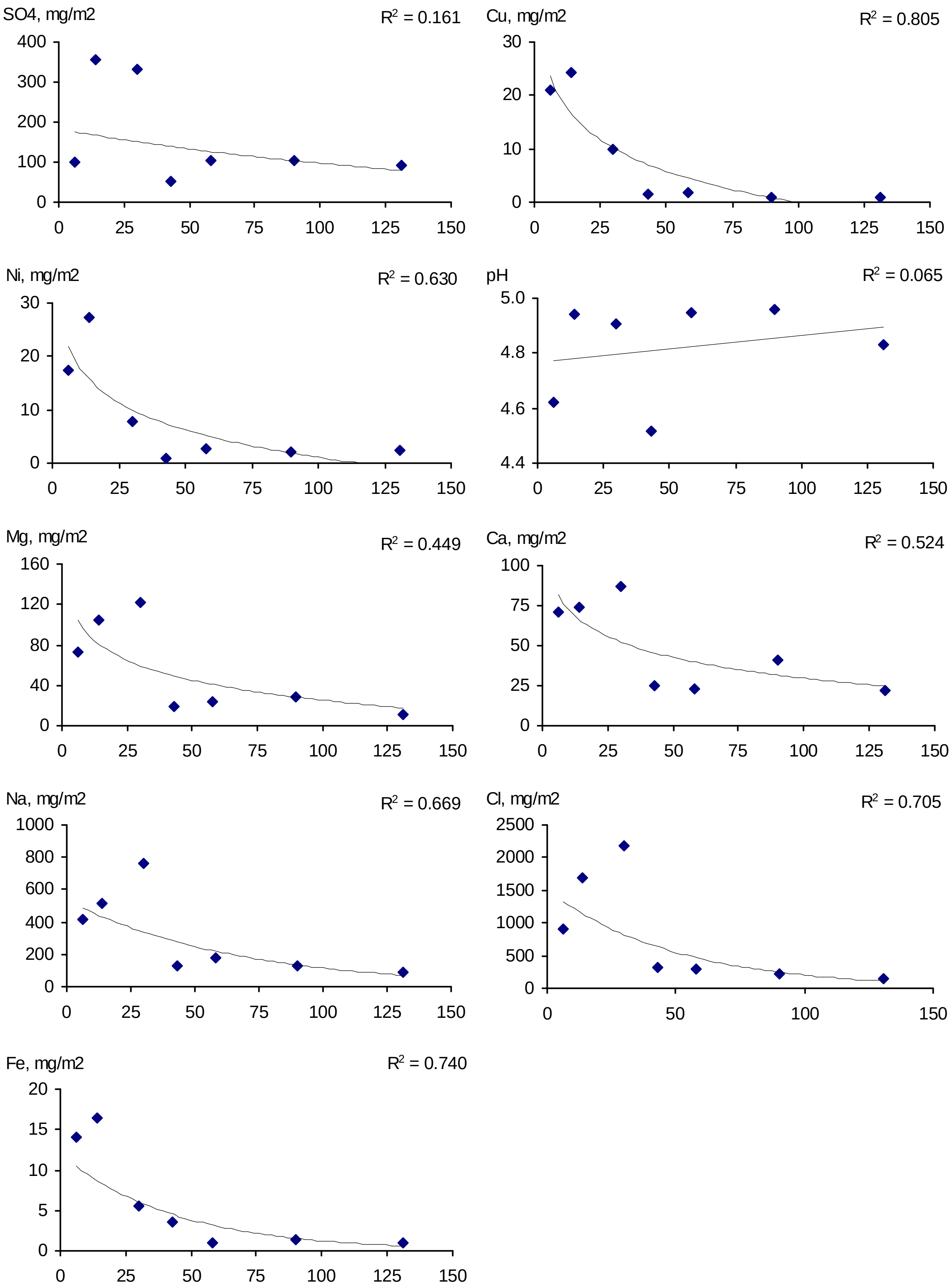

Figure 4.4 Relationship between the annual deposition of SO4-S, Cu, Ni, Mg, Ca, Na, Cl and Fe and mean annual pH in the open (bulk deposition) and the distance to the Nikel smelters in kilometers.

Table 4.3 Distance from the emission source, and annual precipitation (inside the tree stand), average pH and deposition of metals, cations and anions in stand throughfall at the plots in Russia, Norway and Finland in 2004-2005.

Plot	Distance, km	Precip., mm	pH	Cu mg/m^2	Ni mg/m^2	SO_4-S mg/m^2	Zn mg/m^2	Fe mg/m^2	Al mg/m^2
RUS1	6	396	4.60	19.2	13.9	145	4.3	13.7	8.0
PB	14	577	4.81	27.1	30.7	447	25.3	19.8	12.7
S05	17	497	4.57	19.2	13.9	145	4.3	13.7	8.0
N11	30	640	5.04	11.9	12.1	401	4.1	7.4	11.4
RUS0	43	463	4.52	2.2	1.5	116	4.9	7.6	7.2
F-3	58	414	4.83	1.7	2.5	191	6.6	3.1	8.6
F-10	90	431	4.91	0.9	2.2	114	6.9	1.4	6.5
F-11	131	431	4.76	0.9	2.2	102	6.7	1.2	7.3

Plot	Distance, km	Na mg/m^2	Cl mg/m^2	Ca mg/m^2	Mg mg/m^2	K mg/m^2	NO_3-N mg/m^2	NH_4-N mg/m^2
RUS1	6	378	812	79	77	97	30.4	87.9
PB	14	805	2225	129	148	529	66.0	78.8
S05	17	378	812	79	77	97	30.4	87.9
N11	30	1374	3405	136	215	465	61.8	50.9
RUS0	43	229	492	63	52	136	49.6	160.6
F-3	58	432	810	79	67	295	32.6	19.5
F-10	90	154	269	49	36	154	30.8	13.4
F-11	131	121	198	45	24	110	47.4	25.4

Table 4.4. Matrix showing the coefficient of determination (R^2) for the relationships between a number of parameters (mean annual deposition or mean annual pH) in bulk deposition and in stand throughfall. The values with a yellow background are statistically significant at the 5% probability level. n = 8.

Bulk deposition

	Cu	Ni	Fe	SO_4-S	pH	Mg	Ca	Na
Cu								
Ni	0.974							
Fe	0.986	0.965						
SO_4	0.619	0.663	0.547					
pH	-0.019	0.110	-0.132	0.503				
Mg	0.766	0.713	0.697	0.893	0.223			
Ca	0.794	0.717	0.729	0.797	0.162	0.971		
Na	0.672	0.596	0.590	0.857	0.199	0.983	0.943	
Cl	0.675	0.631	0.604	0.923	0.236	0.983	0.919	0.984

Stand throughfall

	Cu	Ni	Fe	SO_4-S	pH	Mg	Ca	Na
Cu								
Ni	0.953							
Fe	0.457	0.296						
SO_4-S	0.601	0.758	0.179					
pH	-0.143	0.045	-0.346	0.547				
Mg	0.557	0.621	0.414	0.909	0.518			
Ca	0.676	0.752	0.395	0.953	0.417	0.968		
Na	0.458	0.530	0.362	0.887	0.588	0.991	0.942	
Cl	0.507	0.595	0.356	0.922	0.572	0.996	0.957	0.994

The annual deposition of base cations (Ca, Mg, K and Na) and the anion Cl was considerably higher on the plots closest to the sea, i.e. plots RUS1, PB and NII. However, these plots are also the closest to the smelters. Due to the extremely strong correlation between Ca and SO_4, and between Na and Cl (Table 4.4), we can assume that most of the Mg and Na is primarily of marine origin. The deposition of Ca and K, on the other hand, is most probably derived from dust emissions from the smelters and power stations at Nikel.

Deposition in the area is characterised by occasional peaks, with relatively high concentrations of Cu, Ni and sulphate (Fig. 4.5); the peaks are primarily determined by the wind direction. However, on some of the monitoring plots (e.g. plots in Finland), the Cu and Ni concentrations were extremely small, and in many cases below the limit of quantification for the analytical equipment.

Coniferous trees are known to effectively filter dry deposition from the atmosphere, and the concentrations of elements are normally considerably higher (except for nitrogen compounds) in stand throughfall than in bulk deposition. However, there were relatively small differences between the deposition of Cu and Ni in bulk deposition and stand throughfall on the individual plots (Tables 4.3 and 4.4), presumably because the stands are of low density and the trees relatively short. Sulphate was an exception to this, almost certainly due to the interception of sulphate containing aerosols of marine origin (Fig. 4.5).

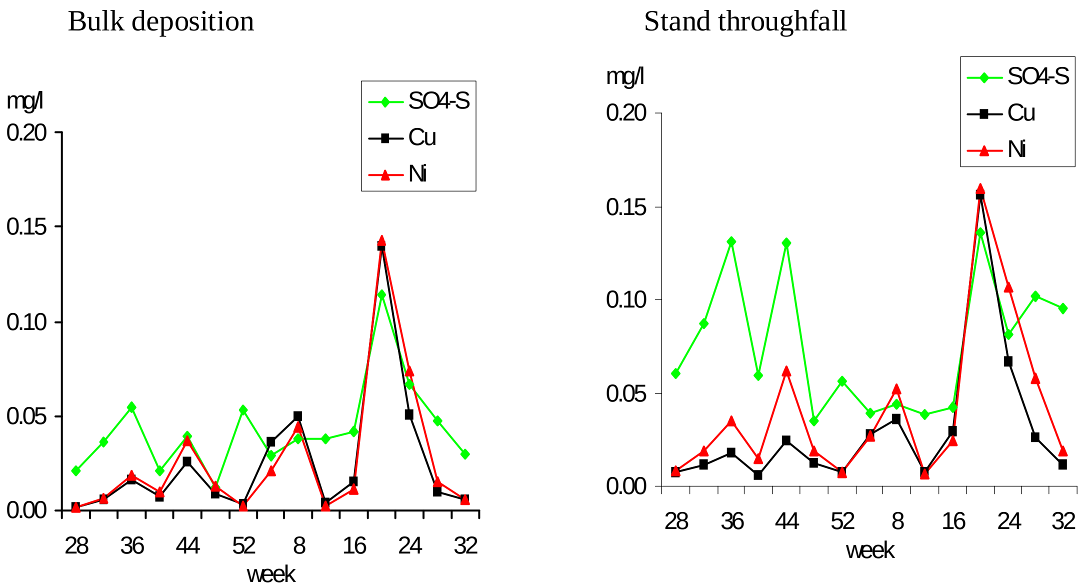

Figure 4.5 Copper, nickel and sulphate concentrations in bulk deposition and stand throughfall at Plot PC in Norway during the period 1.6.2004–8.8.2005. The measured sulphate concentrations have been divided by 10 in order to make comparison of the timing of the peaks easier.

References

ICP Forests, 2005, Manual, Part VI, Measurement of deposition (http://www.icp-forests.org/Manual.htm).

Lindroos, A-J., Derome, J. and Derome, K., 2007. Open area bulk deposition and stand throughfall in Finland during 2001-2004. In: Merilä, P., Kilponen, T. & Derome, J. (eds.). Forect condition monitoring in Finland –National report 2002-2005. Working Papers of the Finnish Forest Research Institute 45. pp. 81-92. http://www.metla.fi/julkaisut/workingpapers/2007/mwp045.htm

4.3 Crown condition

Crown condition is a term describing the overall vitality of a tree. The main components of crown condition are crown density and crown colour. As there was no variation in crown colour on the plots in the area, only the crown density results are reported here.

Scots pine

The crown density was higher on the moderately polluted Norwegian plots (> 90%) in both 2004 and 2005 than on the heavily polluted Russian plots (< 80%), although relatively low crown density was also recorded on the reference plots in Russia (RUS-0) and in Finland (Table 4.5).

Table 4.5 Crown density assessments of Scots pine. The Finnish observations (FL4 to FL6) are means of the corresponding lines 4, 5 and 6. These observations were transformed to crown density by subtracting defoliation from full crown density (100% - ds).

Year	FL-4	FL-5	FL-6	PA	PB	PC	PD	RUS-1	RUS-2	RUS-0
2004				91.8	92.2	93.7	92.5	75.3	79,0	79,0
2005	74.5	79.6	85.3	91.8	92.2	92.5	93.7			
1996*				90.9	95.5	93.6	93.6	**82.9		

* Aamlid et al. 2000
** 1995 values

The striking cross-border difference in crown density may reflect a combination of differences in climate, soil conditions and pollution. The Finnish plots are the least exposed to the deposition of pollutants. However, compared with the Norwegian-Russian area, they are located in an area with a relatively high elevation and nutrient-deficient bedrock, and this may explain the poor crown condition (Merila et al. 1998, De Vries et al. 2000, Ewald 2005).

In a previous study, including a subset of the plots in Norway and Russia (PA, PB, PC, PD, RUS-1), it was concluded that crown condition was negatively affected by pollution (Aamlid et al. 2000). A similar result was obtained in the present survey, and there has also been a reduction in crown density on the plot in Russia subjected to a pollution load (RUS-1). The Russian reference plot (RUS-0) may not be representative as the trees are relatively old and severely attacked by *Peridermium pini*, which has undoubtedly reduced the overall stand vitality and crown density (Michael Gytarsky, personal communication). Thus, there are indications that pollution has reduced the crown density of Scots pine in the border area (cf. Kandler and Innes 1995), but the data are not conclusive.

Birch

Crown density in birch was, in general, assessed on only a small and varying number of trees on each plot, due to the low presence of birch on many of the plots, especially on the north-south gradient. Therefore the results should be considered as only tentative.

Crown density in birch declined along the west-east gradient and appears to be negatively affected by the emissions (Table 4.6). The north-south gradient also included plots located close to the smelter (N6, S3, S5), but these plots had comparably high crown density values (Table 4.7). The results for the two gradients are therefore somewhat conflicting, and the low crown density on the Russian reference plot (RUS-0) cannot be explained in terms of the impact of pollution. Thus the question of whether crown density in birch is negatively influenced by pollution on the area is still open. Being a deciduous tree, birch is expected to be less sensitive than pine to SO_2 pollution (Neuvonen 2001, Kozlov 1992), and this may be what our dataset reflects.

Table 4.6 Crown density assessments of birch, west-east gradient, 1995-2004.

Year	PA	PB	N11	RUS-1	RUS-2	RUS-0
1995	93.6	94.1		56.2		
1998	91.6	91.9		58.2	59.9	51.1
2004	92.5	91.9	81.0	64.2	64.1	58.3

Table 4.7 Crown density assessment of birch, north-south gradient in 2004

Year	N11	N06	S03	S05	S10
2004	81.0	90.1	91.8	90.6	90.3

References

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De Vries, W., Klap, J.M. and Erisman, J.W. 2000. Effects of environmental stress on forest crown condition in Europe. Part I: Hypotheses and approach to the study. Water, Air, and Soil Pollution 119: 317-333.

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Kandler, O. and Innes, J.L. 1995. Air pollution and forest decline in central Europe. Environmental pollution 90: 171-180.

Kozlov, M. V. 1992. pollution-induced changes in the birch population structure in Kola Peninsula, Northern Russia. In: Disturbance Related Dynamics of Birch and Birch Dominated Ecosystems, pp. 51-53. Nordic Symposium, Illugastathir, Fnjóskadalur, Iceland 18-22 september 1992. Iceland Forest Research Station.

Merila, P, Lindgren, M, Raitio, H and Salemaa, M. 1998. Relationships between crown condition, tree nutrition and soil properties in coastal *Picea abies* forests (western Finland). Scandinavian Journal of Forest Research 13: 413-420.

Neuvonen, S. 2001. Pollution-induced changes in mountain birch forests, pp 331-342. In: Wielgolaski, F.E.(ed.): Nordic Mountain Birch Ecosystems. 390 pp. Man and Biosphere series. Vol. 27.

4.4. Stand growth

Growth of the Scots pine stands has been calculated as the relative increase in the increment of basal area, height and volume between 1998 and 2004 (Table 4.7). The basal area increased by between 10 and 38%. The largest increase occurred on plots RUS-1 and RUS-2 in Russia, close to the smelter at Nikel, and the smallest increase on reference plot RUS-0 in Russia. The difference between the plots in Norway was small and unrelated to distance from the smelter. The height increment increased by between 7 and 16%. The highest and lowest increment occurred on the two plots furthest from the emission sources, PA and RUS-0, respectively (Table 4.7). The difference in height increment between the other plots varied by only 4%, the lowest increment occurring on plot RUS-1 close to Nikel. The volume increment increased by between 16 and 54%. However, when the volume increment was calculated on the basis of the increment in basal area and height, there was no spatial pattern for this parameter.

Table 4.7 Relative change between 2004 and 1998 for basal area (rBA), tree height (rTH) and tree volume (rV). Different letters indicate significant differences at the 5% level between plots.

	PA	PB	PC	PD	RUS-1	RUS-2	RUS-0
rBA	1.271b	1.257b	1.269b	1.283ab	1.377a	1.338ab	1.0096c
rTH	1.162a	1.144a	1.151a	1.159a	1.122b	1.156a	1.070c
rV	1.431ab	1.369b	1.408c	1.428ab	1.541a	1.478ab	1.160c

In conclusion, despite the large variation between the plots, there are no indications that pollution from the smelters is having a negative effect on the growth of Scots pine, not even on the plots in the immediate vicinity of the smelters. A relatively high correlation has been reported in Norway spruce between crown condition and growth (Solberg 1999). In our data the correlation for Scots pine was extremely low ($r^2 \leq 0.14$), which indicates that crown condition is not related to the growth of Scots pine in the border area.

4.5 Ground vegetation

The ground vegetation, defined as all lichens, bryophytes and vascular plants (for woody species only those with a height below 50 cm), was assessed on the monitoring network in 2004, and then compared with earlier analyses carried out on the original networks (Aamlid et al. 2000, Yoccoz et al. 2001).

4.5.1 Sampling units

The common sample unit for assessment of the species abundance and composition of the ground vegetation on all the plots was a 1 x 1 m quadrat. However the number of quadrats analysed on the individual plots varied between the different networks.

1. On the eight plots of the Skogforsk-NINA-VNIIPRIRODA-IGCE monitoring network there were originally twenty 1 x 1m quadrats randomly distributed within the inner area (Fig. 4.1, section 4.1). Ten of the original 20 quadrats on each of the Norwegian plots (PA, PB, PC and PD) were randomly selected as monitoring sites in 2004, while all of the 20 quadrats were assessed on the Russian plots (RUS0, RUS1 and RUS2). The total number of quadrats was therefore 100. Data from 1994-1996 were available for all the quadrats.

2. On the 5 plots selected from the NINA-NGU-INEP-METLA monitoring network (S3, S5, S10, N6 and N11) one 1 x 1 m quadrat was marked out at the centre of each sub-plot (A, B, C, D and E), giving five quadrats per plot (Fig. 4.2, section 4.1). A total of 25 quadrats were analysed in 2004. Percentage cover data from 2000 were available for all the quadrats.

3. On the nine selected plots from the Lapland Forest Damage Project network one of the four circular plots forming a cluster (Fig. 4.3, section 4.1) was selected for assessment of the ground vegetation. A total of 7–12 vegetation quadrats (1 x 1 m) were systematically marked out on the plot along two transects running S-N and W-E. A total of 87 quadrats were analysed in 2004 for the first time.

Thus, a total of 212 vegetation quadrats, covering a gradient ranging from heavily affected areas to areas with almost no pollution impact, were assessed in 2004.

4.5.2 Species composition of the ground vegetation in 2004

The selected plots represented eutrophic dry to medium dry pine and birch forests with naturally occurring *Cladonia* lichens, hepatics mainly *Barbilophozia* spp., *Dicranum* spp. and *Pleurozium schreberi* mosses and small dwarf shrubs of *Empetrum nigrum*, *Vaccinium* spp. and *Ledum palustre*. A number of herbs, such as *Linnea borealis, Listera cordata, Pedicularis lapponica* and *Trientalis europaea*, and the grass *Deschampsia flexuosa*, were the most common species in the medium dry forests, while lichens and bryophytes dominated in the dryer forests.

A detrended correspondence analysis DCA (Hill 1979, Hill & Gauch 1980) of the species on the 212 quadrats showed that there was a gradient in the analysed vegetation from dry vegetation dominated by lichens to medium dry vegetation with more dwarf shrubs and herbs (Figure 4.6). The vegetation on the Norwegian plots (PA-PD, N11) was very similar to that on the Russian reference plots (S10 and RUS0), far to the south of the Nickel smelter, and also similar to that on many of the Finnish sample plots. However, several of the Finnish plots reflected a dryer vegetation type more dominated by reindeer lichens and cup lichens. The Norwegian, Finnish and the Russian reference plots all probably represent naturally occurring vegetation with a very low pollution impact.

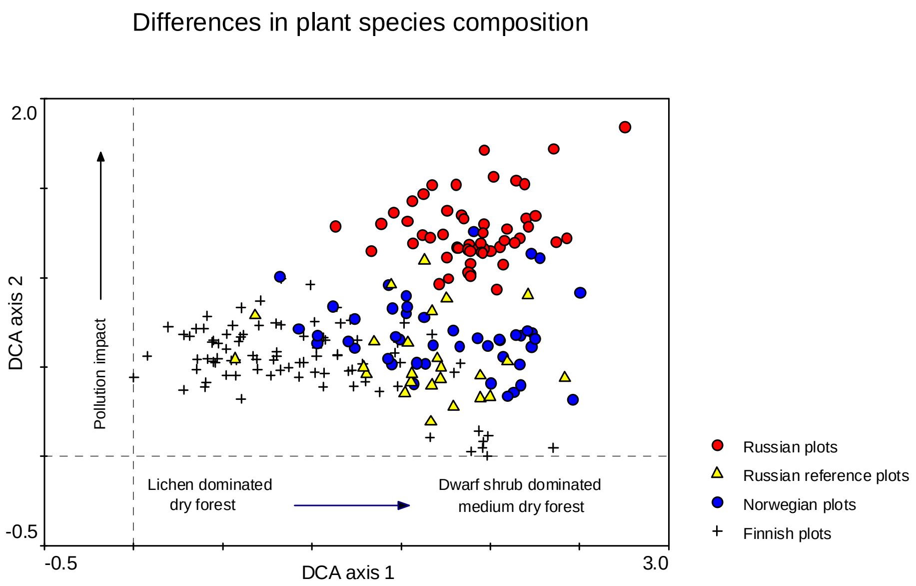


Figure 4.6 Detrended correspondence analysis (DCA) of a total of 212 quadrats (sample plots), axis 1 and 2, performed with CANOCO version 4.5 (ter Braak & Smilauer 2002). Sample plots that are situated close together have a very similar species composition and, correspondingly, those far apart have a very different one.

The species composition of the ground vegetation on the Russian plots in the vicinity of the Nickel melter (RUS-1, RUS-2, S-3 and S-5) was, however, very different from that on the other plots in the monitoring network (Figure 4.6, red plots). In general, they lacked most of the bryophytes, and the lichen cover was very sparse. This is probably an effect of air pollution on these plots. However, the vegetation on the Russian plot to the north (N6) was distinctly more vigorous, and was dominated by *Vaccinium myrtillus*, *Cornus suecica*, *Gymnocarpium dryopteris* and *Deschampsia flexuosa*, indicating less pollution impact at this site.

4.5.3. Differences in the vegetation along the east-west transect in 2004

The plots along the E-W transect were selected for a more detailed evaluation in order to minimize the effect of bio-geographical variation on the vegetation pattern, and to quantify the impact, if any, of air pollution. The length of the study transect is 63 km, and it runs from the Petsenganikel smelter through eastern Finnmark to Finnish Lapland. The distance of the plots from the smelter are:

Plot	km
RUS-2	3.5
RUS-1	6
PC	7.5
PD	12
PB	14
PA	22
P513	41
P542	51
P561	63

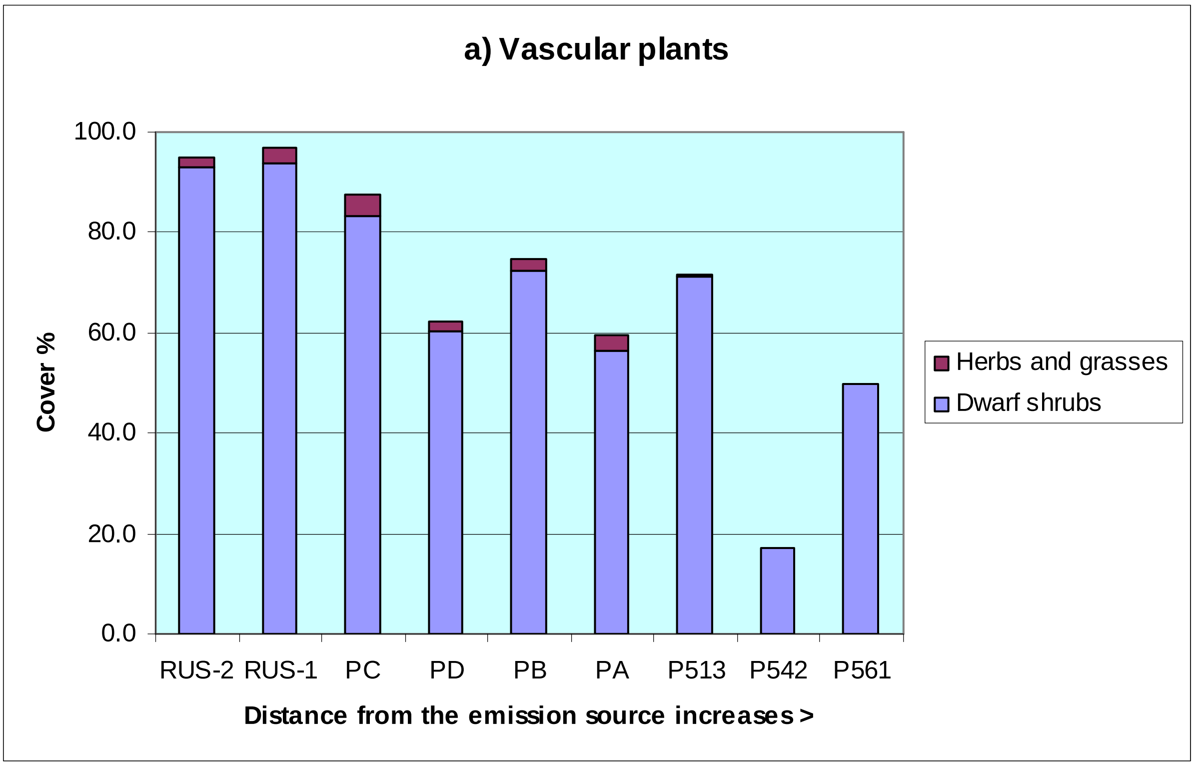
The plotwise average percentage cover was calculated for vascular plants, bryophytes and lichens (Fig. 4.7, a-c).

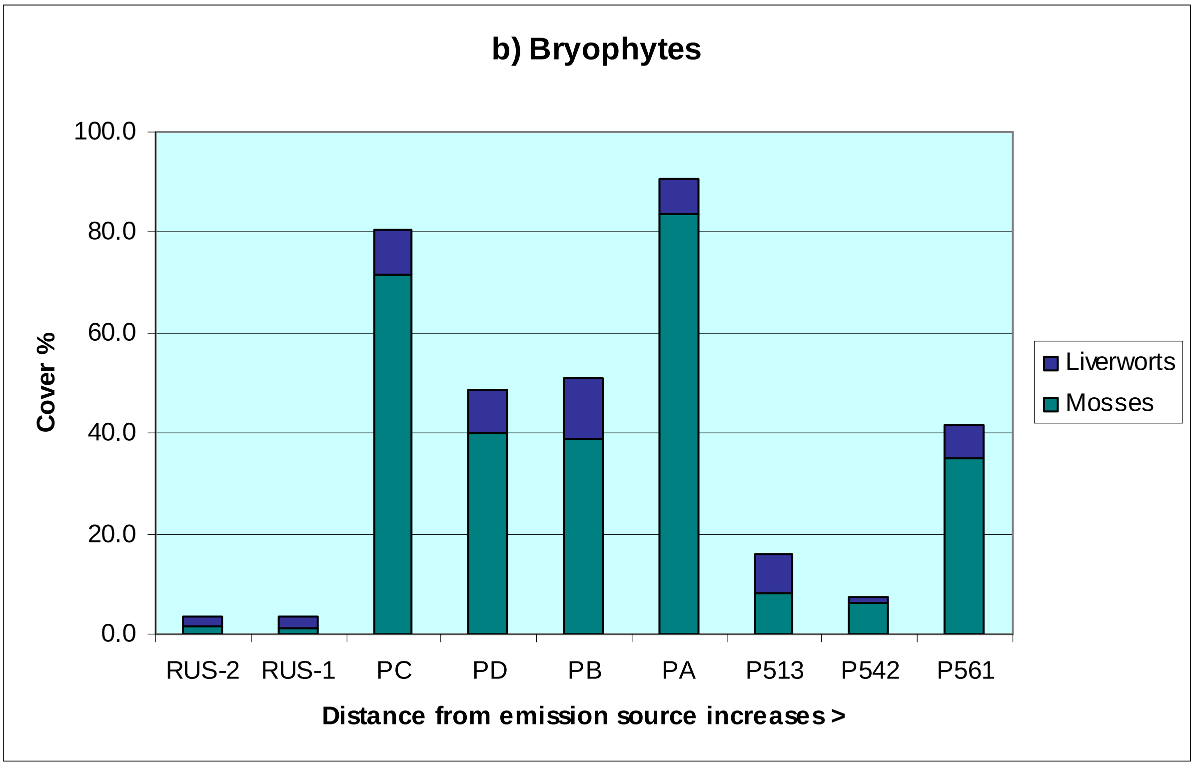
The cover of vascular plants was the highest on the Russian plots and decreased on moving westwards (Fig. 4.7, a). Dwarf shrubs formed the major group within the vascular plants. Herbs and grasses were the most abundant on plots RUS-1 and PC, but their percentage cover was very low. Dryer growing conditions explained the lower abundance of vascular plants on the Finnish plots.

The abundance of bryophytes was the highest (average cover 40 - 84 %) on the Norwegian plots (Fig. 4.7, b). Similarly, the cover of liverworts was the highest on the Norwegian part of the transect. Bryophytes were almost absent on the Russian plots, indicating an impact of pollutants. However, four taxons of liverworts were found on the two Russian plots, and they had even a higher cover (2 %) than that of mosses (1.5 %). The cover of the moss layer varied on the Finnish plots depending on the moisture level of the individual sites.

The cover of terricolous lichens increased on moving to the west along the transect (Fig. 4.7, c). The cover of reindeer lichens (*Cladonia* spp.) on the Finnish plots was about 16 % and that of cup lichens 12 %. In contrast, the lichen layer was very scarce on the Russian plots (3 %) and mainly consisted of pioneer cup lichens. The Norwegian plots also had a relatively low abundance of lichens compared to the situation on the Finnish plots. The group of other lichens included leather lichens (*Peltigera* sp.), which occurred sporadically on the plots.

The composition and the relative abundance of the plant species has changed in the vicinity of the Petsenganikel smelter. On the Russian plots, the ground vegetation was characterised by dwarf shrubs, which are relatively resistant to heavy metals and other pollutants. The common forest bryophytes (e.g. *Pleurozium schreberi*) and reindeer lichens, which are known to be affected adversely by air pollutants, were missing on the plots near the smelter. On the other hand, some pioneer bryophytes and cup lichens were growing on the disturbed and polluted soil. The increase in the abundance and number of bryophyte species on the Norwegian plots was probably due to the lower pollution load. The composition and abundance of the species on the lichen heaths on the Finnish plots mainly reflected the characteristics of the dryer growing sites and reindeer grazing, rather than the effect of air pollutants. However, increased heavy metal and sulphur concentrations were found in mosses and lichens on the Finnish plots (see sections 4.8.1 and 4.8.2).


a) Vascular plants
100.0
80.0
60.0
40.0
20.0
0.0
Cover %
RUS-2 RUS-1 PC PD PB PA P513 P542 P561
Distance from the emission source increases >
Herbs and grasses
Dwarf shrubs


b) Bryophytes
100.0
80.0
60.0
40.0
20.0
0.0
Cover %
RUS-2 RUS-1 PC PD PB PA P513 P542 P561
Distance from emission source increases >
Liverworts
Mosses

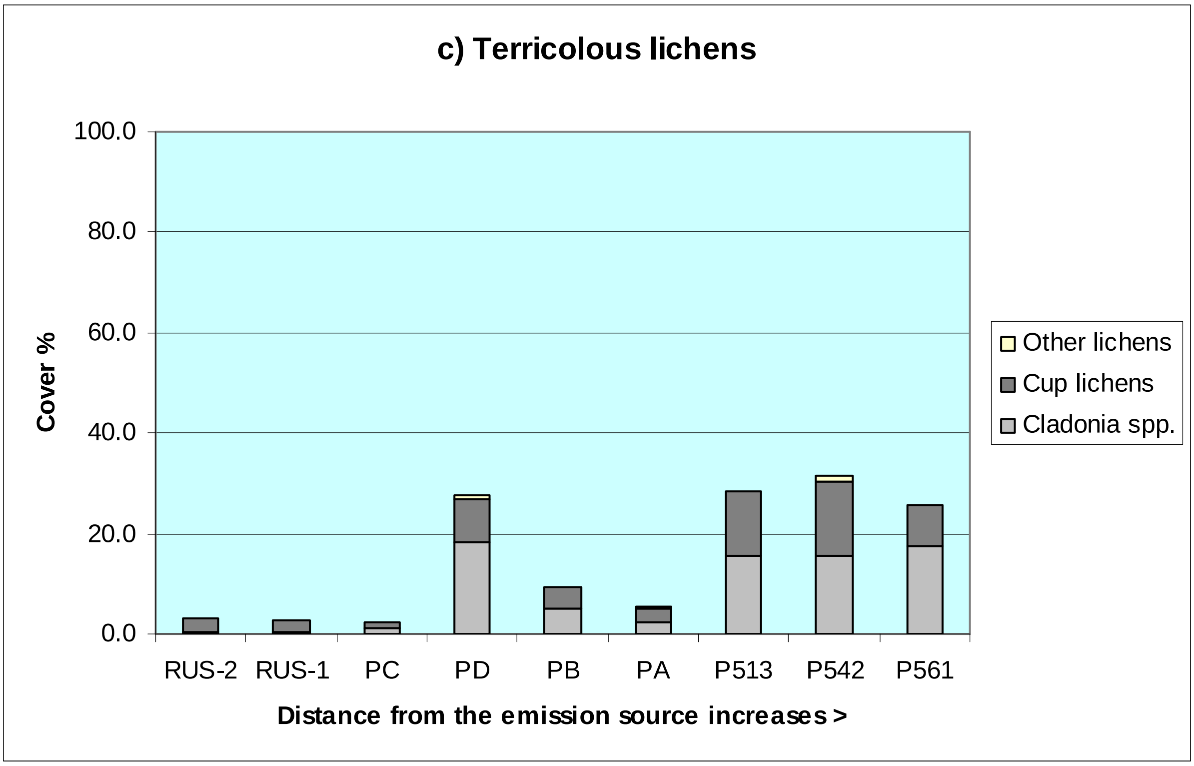


Figure 4.7 The average cover (%) of a) vascular plants, b) bryophytes (mosses and liverworts) and c) terricolous lichens on the sample plots along the east - west transect.

4.5.4 Preliminary results of ground vegetation analysis on the long-term sample plots along the east-west transect (1994, 1995, 1998 and 2004 surveys)

The monitoring plots where ground vegetation data were available from 1994, 1995, 1998 and 2004 were located at various distances from the pollution source (see Fig. 2.1). The plots were RUS0 (the most remote site), PA, PB, PD, PC, RUS1 and RUS2. Analysis of the ground vegetation was carried out once on 20 randomly selected 1 x 1m quadrats on all the plots during 1994-1998. In 2004 the analysis was repeated on all the quadrats on the Russian plots, and on 10 randomly selected quadrats on the Norwegian plots. The analysis included records of the species composition of dwarf shrubs, herbs, grasses, lichens and bryophytes, and their percentage cover. Assessment of the species composition, species abundance (number of species per unit area) and average percentage cover was made for each species community. A species community is defined as a group of species that occupies a similar spatial and temporal location. The following communities were identified: trees and shrubs, dwarf shrubs, herbs and grasses, mosses, liverworts and lichens.

Species composition

The dwarf shrub community on all the sample plots included *Empetrum nigrum* ssp. *hermaphroditum*, *Vaccinium myrtillus*, *Vaccinium vitis-idaea* and *Ledum palustre*. *Vaccinium uliginosum* was also present on plots RUS0, RUS1 and RUS2, although its occurrence and percentage cover were minor. The percentage cover of *Empetrum nigrum* ssp. *hermaphroditum* and *Vaccinium vitis-idaea* was notably higher on plots RUS1 and RUS2 than on the other plots. For herbal communities, *Linnaea borealis* and *Deschampsia flexuosa* had the highest occurrence and percentage cover on all the plots. Low values for percentage cover and occurrence were typical for the other herbal species.

Pleurozium schreberi, *Pohlia nutans* and *Polytrichum juniperinum* were found within the moss communities on all the plots. Their occurrences abruptly dropped in conditions of increased pollution (RUS1 and RUS2 plots). *Pleurozium schreberi* was the most dominant moss on the RUS0, PA, PB, PC and PD plots. However, its perecentage cover and occurrence were significantly lower on the RUS1 and RUS2 plots. Some species (*Dicranum* spp., *Hylocomium splendens*, *Plagiothecium laetum*) occurred only on the RUS0, PA, PB, PC and PD plots. The reason for the absence of these species on the RUS1 and RUS2 plots may be the high level of pollution on these plots.

The liverwort community was represented by *Barbilophozia* spp. and *Lophozia ventricosa*, and they occurred on all the plots. However, their occurrence and percentage cover was notably lower on the RUS1 and RUS2 plots.

The lichens *Cladonia arbuscula*, *C. chlorophaea*, *C. crispata*, *C. furcata*, *C. rangiferina*, *C. gracilis* and *C. deformis* were found on all the plots. However, their occurrence and percentage cover significantly decreased on the RUS1 and RUS2 plots. Some lichen species were missing on the RUS1 and RUS2 plots. These changes in lichen community are most probably due to the effects of pollution from the smelters.

Species abundance (number of species per unit area)

The lowest species abundance values occurred on the RUS1 and RUS2 plots, which are the closest to the pollution source. The decrease in total abundance was due to the Fig. 4.8. This is obviously due to the natural succession that occurs in forest ecosystems. In contrast, the percentage cover of lichens, mosses and liverworts decreased on plot RUS1 or remained at approximately the same level on plot RUS2, both of which are subjected to higher levels of pollution (Fig. 4.8), and a reduction in the number of lichens, liverworts and mosses (Table 4.8). This is clearly evident from the average and maximum number of species per 1 m^2. The species abundance of dwarf shrubs and herbs was relatively constant on all the sample plots. There were only insignificant changes in the species abundance in 2004 compared to the situation in 1994/1995 and 1998. The differences between the abundance values on the Norwegian sample plots in different assessment years were presumably due to the differences in sampling size: only 10 quadrats were analyzed on each plot in 2004, but on 20 quadrats in 1994 and 1995.

Average percentage cover of species communities within the plots

There was a decrease in the percentage cover of lichens, liverworts and mosses on the RUS1 and RUS2 plots (Table 4.8). However, the cover of dwarf shrubs was significantly higher than that on the other plots.

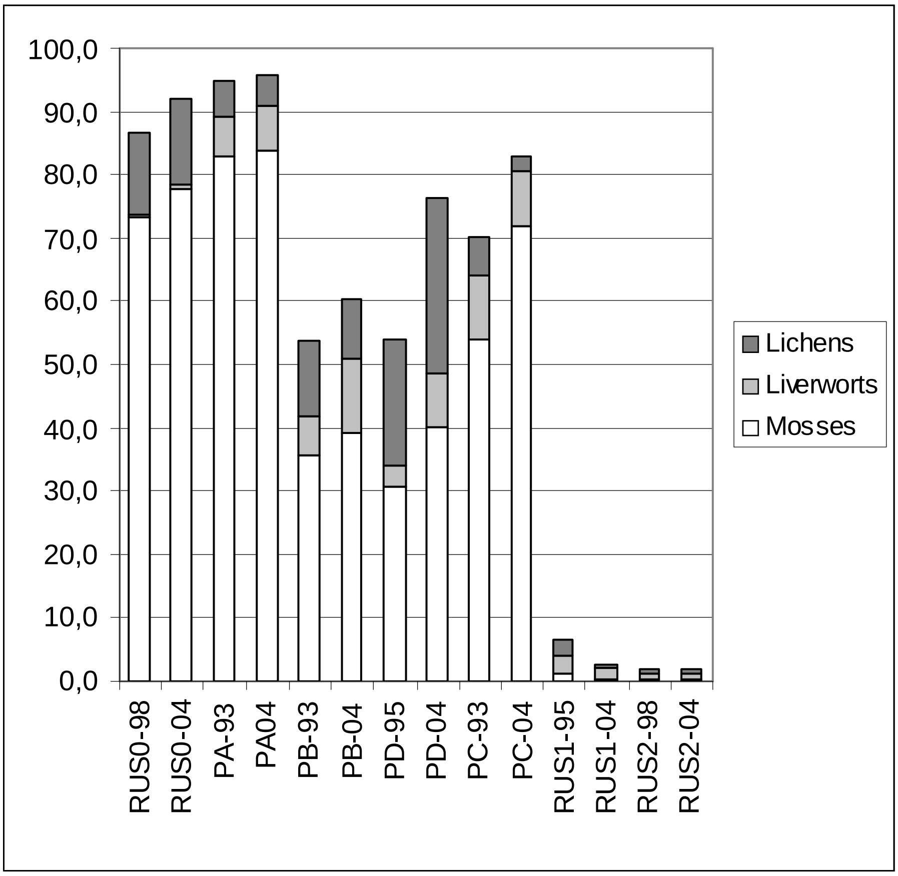


Figure 4.8 The projective cover of lichens, liverworts and mosses over the plots.

In 2004, the cover of mosses on the RUS0, PA, PB, PC and PD plots, which are subjected to relatively insignificant levels of pollution, had increased higher. The cover of lichens and liverworts changed to only a very small extent (Table 4.9).

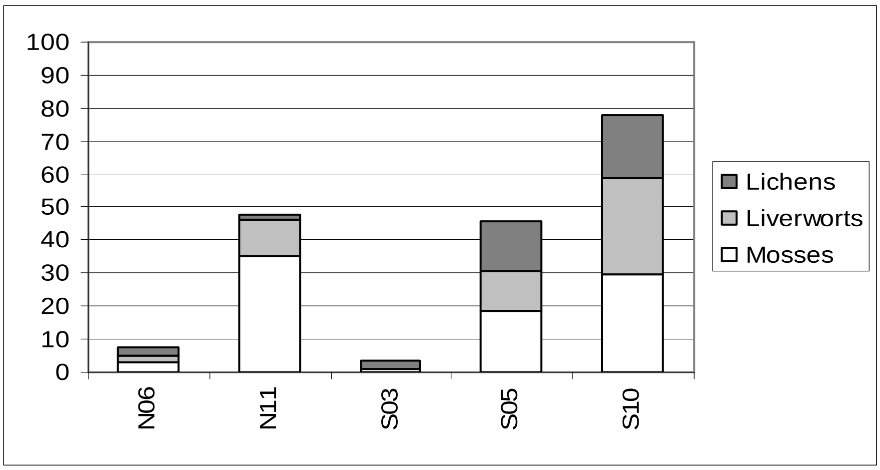


Figure 4.9 The projective cover of lichens, liverworts and mosses on the plots.

Table 4.8 Species abundance (number of species per unit area) of different vegetation communities within the plots along the east-west pollution gradient in two different years. Average and maximum (in parentheses) number of species per m^2.

Plot Year	RUS0 1998	RUS0 2004	PA 1993	PA 2004	PB 1993	PB 2004	PD 1995	PD 2004	PC 1993	PC 2004	RUS1 1995	RUS1 2004	RUS2 1998	RUS2 2004
Dwarf shrubs	3,5 (5)	3,5 (5)	2,9 (4)	1,6 (4)	3,1 (4)	1,6 (4)	3,1 (4)	1,7 (4)	3,4 (4)	1,8 (4)	4,2 (5)	4,2 (5)	4 (5)	3,9 (5)
Herbs & grasses	1,9 (4)	1,5 (4)	1,9 (3)	0,6 (2)	1,7 (4)	0,5 (3)	0,8 (2)	0,2 (1)	1,9 (3)	0,6 (2)	2 (3)	2,1 (4)	1,1 (3)	1,3 (2)
Mosses	5,1 (7)	5,3 (8)	4,6 (9)	2,3 (7)	4,7 (8)	2,4 (7)	4,7 (6)	2,5 (6)	4,6 (7)	2,2 (6)	1,2 (3)	1,3 (3)	2,1 (4)	1,7 (3)
Liverworts	1,3 (3)	1,7 (4)	1,5 (3)	0,7 (2)	2 (3)	2,4 (7)	1,5 (3)	1,8 (5)	1,6 (2)	1,5 (4)	0,7 (2)	0,9 (2)	1,1 (2)	1,5 (5)
Lichens	3,7 (9)	4,1 (10)	4,1 (9)	1,6 (10)	7,5 (12)	3,2 (12)	8,2 (14)	4,7 (15)	3,9 (9)	0,9 (6)	2,3 (7)	2,8 (7)	3,1 (7)	3,1 (7)
Total	15,4 (24)	16 (22)	14,9 (30)	6,7 (21)	19,2 (32)	9,9 (27)	18,7 (31)	11,2 (27)	15,6 (26)	7,1 (19)	10,9 (23)	11,7 (17)	11,5 (17)	11,4 (16)

Table 4.9 The average percentage cover of species communities within the plots long the east-west pollution gradient in two different years.

Plot Year	RUS0 1998	RUS0 2004	PA 1993	PA 2004	PB 1993	PB 2004	PD 1995	PD 2004	PC 1993	PC 2004	RUS1 1995	RUS1 2004	RUS2 1998	RUS2 2004
Dwarf shrubs	30,6	48,1	46,9	56,3	52,0	72,3	41,7	57,8	78,7	82,8	96,3	90,2	89,6	93,4
Herbs & grasses	0,6	0,5	4,4	3,4	2,7	2,3	0,9	1,7	4,7	4,3	3,2	2,0	1,1	1,2
Mosses	73,4	78,0	82,8	83,8	35,8	39,1	30,6	40,2	54,2	71,8	1,3	0,3	0,3	0,3
Liverworts	0,5	0,5	6,4	6,9	6	11,9	3,7	8,4	10,1	8,9	2,9	1,8	0,9	1,0
Lichens	13,0	13,7	5,6	5,3	12	9,4	19,7	27,7	6,1	2,3	2,5	0,3	0,8	0,6

Table 4.10 Average (maximum) number of plant species per m^2 grouped by community.

Plot	N06	N11	S03	S05	S10
Dwarf shrubs	2,6 (3)	3,2 (4)	3,6 (4)	3 (4)	3 (3)
Herbs & grasses	4,2 (5)	3,2 (4)	0,6 (1)	2 (4)	3,8 (4)
Mosses	2,6 (4)	4,8 (7)	0,6 (1)	2,8 (3)	4,6 (6)
Liverworts	1,8 (3)	2,8 (4)	0,4 (1)	3,6 (5)	3,8 (6)
Lichens	2,6 (6)	1,2 (3)	2 (6)	8 (11)	6,8 (9)
Total	13,8 (21)	15,2 (22)	7,2 (13)	19,4 (27)	22 (28)

4.5.5 Preliminary results of ground vegetation analysis on the birch plots along the N-S transect (2004 survey)

The ground vegetation was analysed on 5 randomly selected 1 x 1 m quadrats on each plot. The plots (N06, N11) along the N transect were dominated by dwarf shrubs (*Empetrum nigrum ssp. hermaphroditum*, *Vaccinium myrtillus*, *Vaccinium vitis-idaea*) and herbs (mainly *Cornus suecica* and *Deschampsia flexuosa*). The cover of mosses and liverworts was low, and the contribution of the lichen community small.

The plots (S05, S10) along the S gradient were characterized by dominant dwarf shrubs and an insignificant cover of herbs. Although the moss, liverworts and lichen communities were abundant under unpolluted conditions, the absolute cover percentages were lower than on the pine plots. There was clear degradation of mosses, liverworts and lichens in the vicinity of the emission source, i.e. a decrease in both the percentage cover and species distribution. The lowest percentage cover and species composition of mosses and liverworts occurred on the S03 plot, adjacent to the pollution source (Fig. 4.9 and Table 4.10).

4.5.6 Changes in species occurrence on the Norwegian and Russian plots during the last 4-10 years

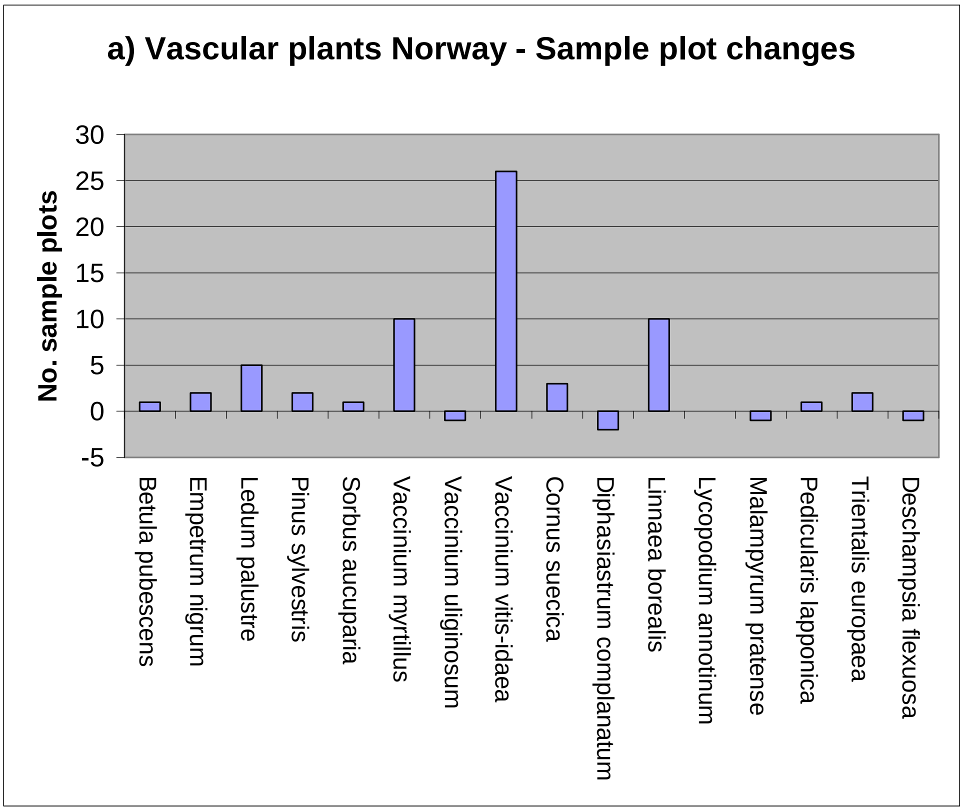
The number of quadrats where the species percentage cover had decreased, remained stable or increased since the first analysis (PA, PB, PC in 1994, PD and RUS1 in 1995, RUS0 and RUS2 in 1998, and all the N and S plots in 2000) were calculated separately for the Norwegian and the Russian plots. The overall change (sum of increased and decreased quadrats) for each species is shown in Fig. 4.10, a–f.

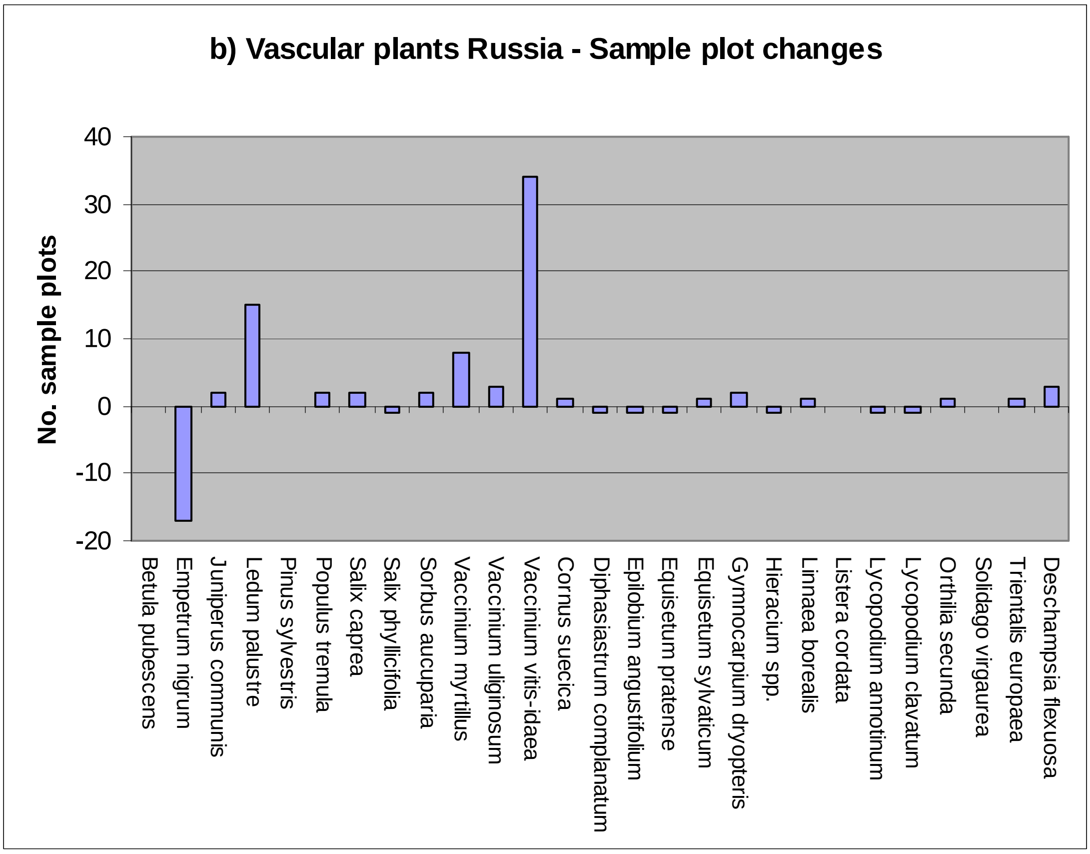
<u>Vascular plants</u>
The abundance of vascular plants was relatively stable on both the Norwegian and the Russian plots (Fig.4.10, a and b). However, there was a major increase in *Vaccinium vitis-idaea* on all the plots. *Vaccinium myrtillus* and *Linnaea borealis* increased slightly on the Norwegian plots, while *Ledum palustre* increased to some extent on the Russian plots. There was no major decrease in vascular plants, apart form the slight decrease in *Empetrum nigrum* on the Russian plots.

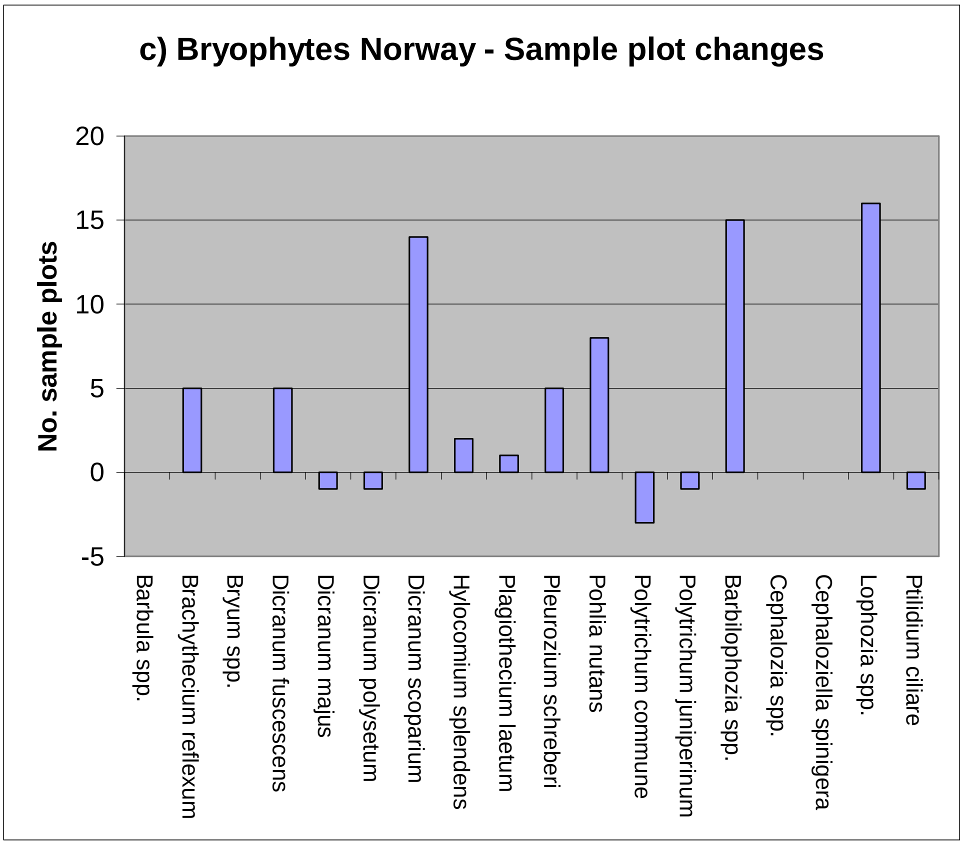
<u>Bryophytes</u>
Several bryophytes increased their percentage cover on both the Norwegian and Russian plots, especially the liverworts *Barbilophozia* spp. and *Lophozia* spp. (Fig. 4.10, c and d). *Pohlia nutans* and *Pleurozium schreberi* also had an increasing cover, especially on the Russian plots, while *Dicranum scoparium* mainly increased on the Norwegian plots.

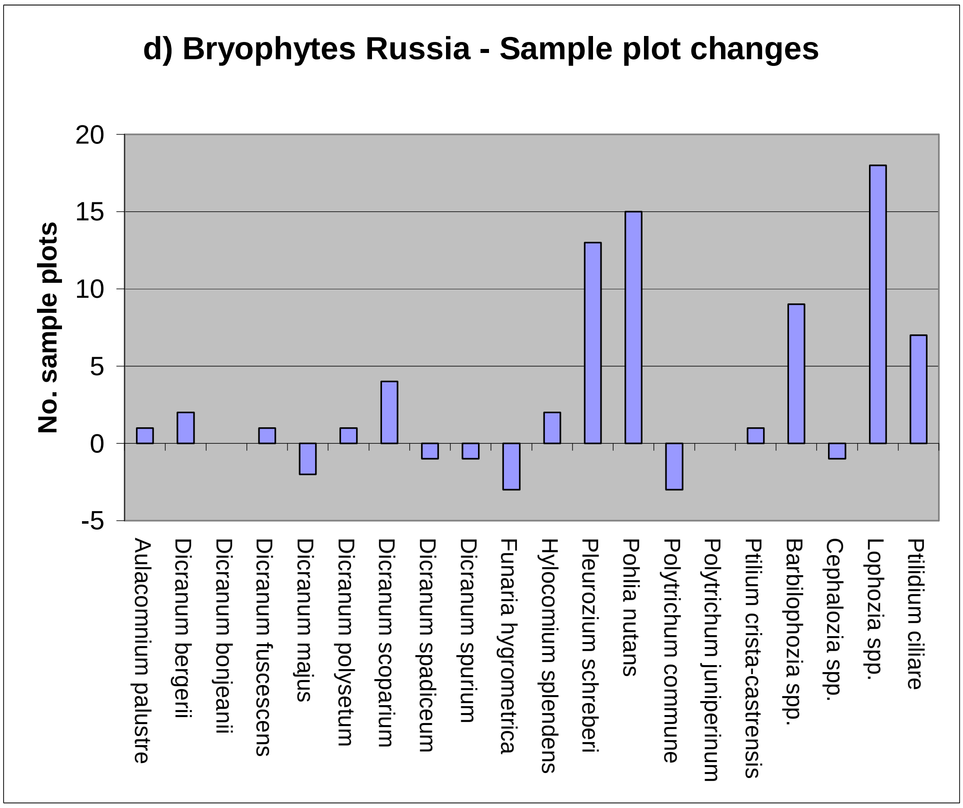
<u>Lichens</u>
Several lichen species either increased or decreased their cover on the Norwegian plots (Fig. 4.10, e). On the Russian plots, however, the cover of lichens mainly increased (Fig. 4.10, f), especially the small cup lichens *Cladonia botrytes*, *Cladonia carneola* and *C. chlorophaea* coll., and the awl-shaped lichens *Cladonia furcata* and *C. gracilis.*

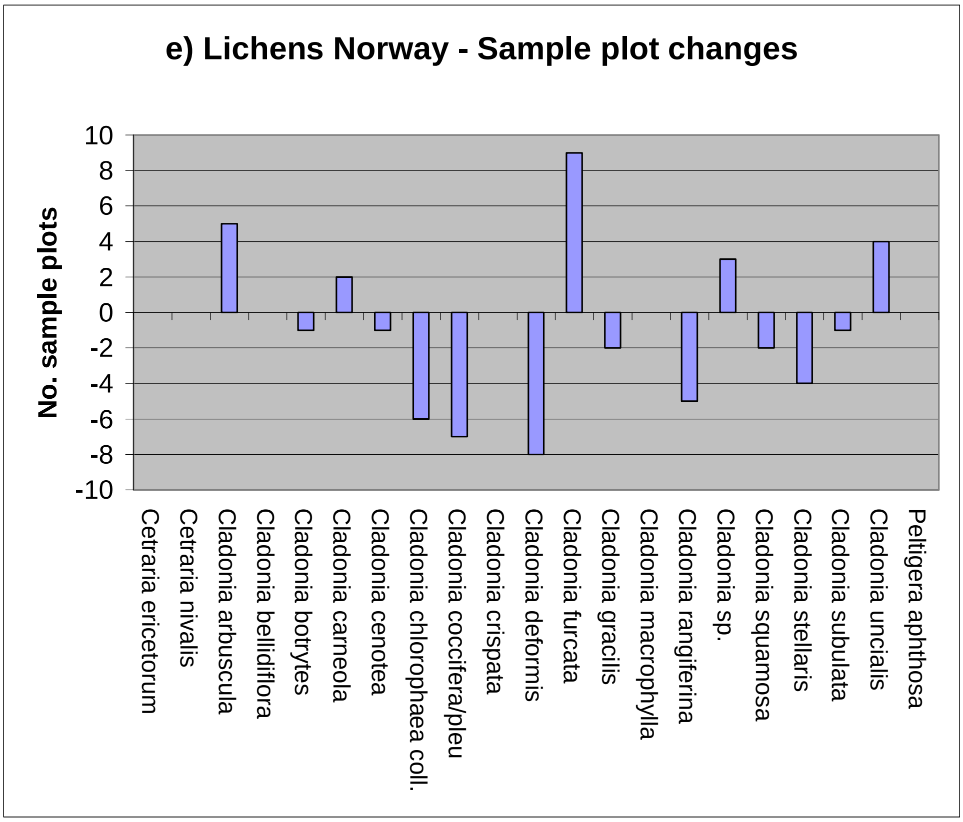
All the minor changes detected between these surveys may be due to year-to-year fluctuations in species abundance or estimation errors in the assessments. However, there are strong indications that several species, especially bryophytes and lichens, are recovering on some of the Russian plots. The changes in the abundance of lichens on the Norwegian plots may also be a result of varying grazing pressure by reindeer.


a) Vascular plants Norway - Sample plot changes
No. sample plots
30
25
20
15
10
5
0
-5
Betula pubescens
Empetrum nigrum
Ledum palustre
Pinus sylvestris
Sorbus aucuparia
Vaccinium myrtillus
Vaccinium uliginosum
Vaccinium vitis-idaea
Cornus suecica
Diphasiastrum complanatum
Linnaea borealis
Lycopodium annotinum
Malampyrum pratense
Pedicularis lapponica
Trientalis europaea
Deschampsia flexuosa


b) Vascular plants Russia - Sample plot changes
No. sample plots
40
30
20
10
0
-10
-20
Betula pubescens
Empetrum nigrum
Juniperus communis
Ledum palustre
Pinus sylvestris
Populus tremula
Salix caprea
Salix phyllicifolia
Sorbus aucuparia
Vaccinium myrtillus
Vaccinium uliginosum
Vaccinium vitis-idaea
Cornus suecica
Diphasiastrum complanatum
Epilobium angustifolium
Equisetum pratense
Equisetum sylvaticum
Gymnocarpium dryopteris
Hieracium spp.
Linnaea borealis
Listera cordata
Lycopodium annotinum
Lycopodium clavatum
Orthilia secunda
Solidago virgaurea
Trientalis europaea
Deschampsia flexuosa


c) Bryophytes Norway - Sample plot changes
No. sample plots
20
15
10
5
0
-5
Barbula spp.
Brachythecium reflexum
Bryum spp.
Dicranum fuscescens
Dicranum majus
Dicranum polysetum
Dicranum scoparium
Hylocomium splendens
Plagiothecium laetum
Pleurozium schreberi
Pohlia nutans
Polytrichum commune
Polytrichum juniperinum
Barbilophozia spp.
Cephalozia spp.
Cephaloziella spinigera
Lophozia spp.
Ptilidium ciliare


d) Bryophytes Russia - Sample plot changes
No. sample plots
20
15
10
5
0
-5
Aulacomnium palustre
Dicranum bergerii
Dicranum bonjeanii
Dicranum fuscescens
Dicranum majus
Dicranum polysetum
Dicranum scoparium
Dicranum spadiceum
Dicranum spurium
Funaria hygrometrica
Hylocomium splendens
Pleurozium schreberi
Pohlia nutans
Polytrichum commune
Polytrichum juniperinum
Ptilium crista-castrensis
Barbilophozia spp.
Cephalozia spp.
Lophozia spp.
Ptilidium ciliare



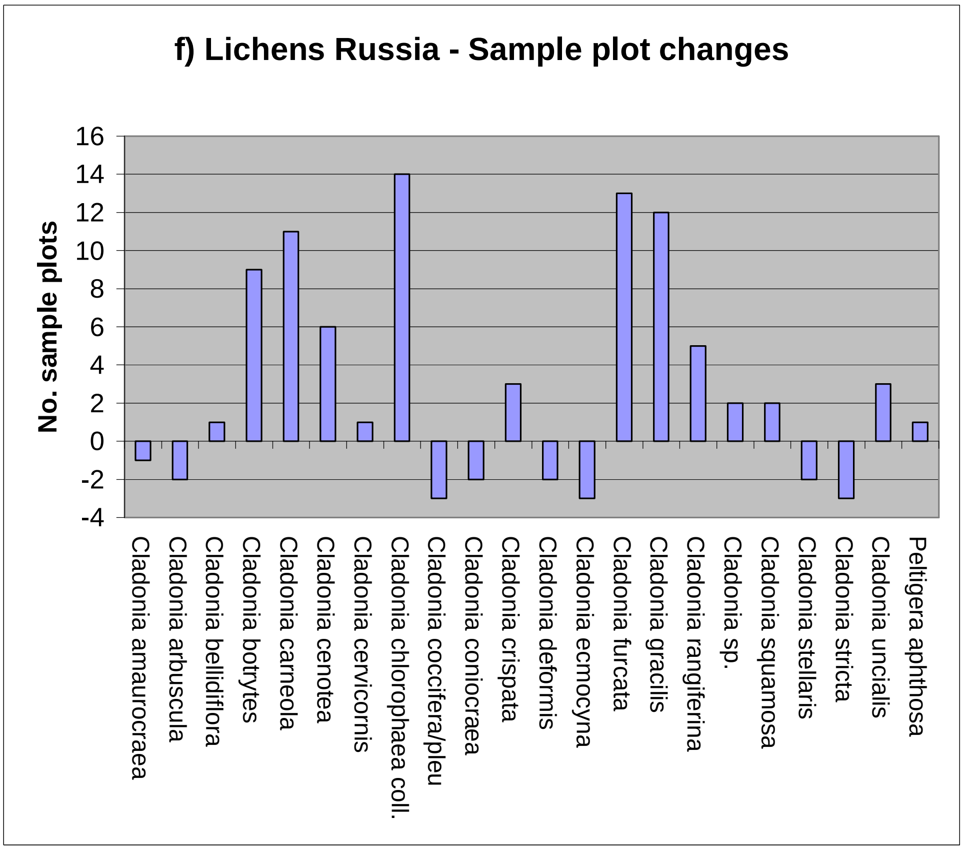


Figure 4.10 Changes in the abundance of individual species within the quadrats (plots) in Norway and Russia, based on two different years of sampling (4-10 year intervals). Number of plots shows the overall change (the sum of plots where the species has increased or decreased) for a, b) vascular plants, c, d) bryophytes, e, f) lichens.

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4.6 Epiphytic lichens

Birch stems

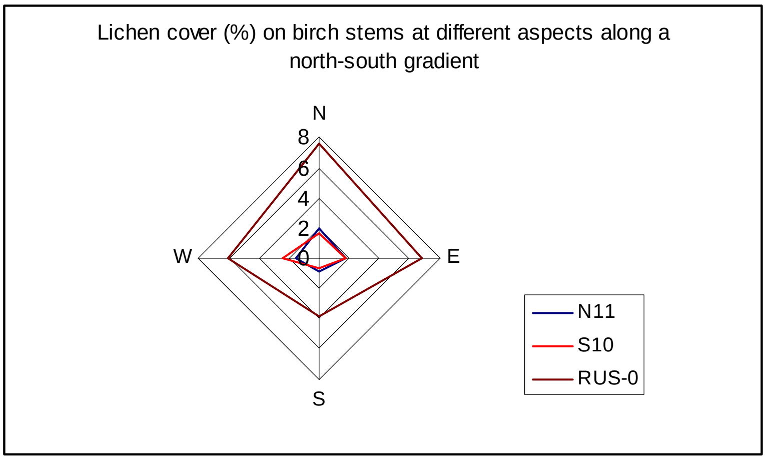
The most common lichens on birch stems in the area were *Hypogymnia physodes* and *Melanelia olivacea*. Epiphytic lichens are sensitive pollution indicators, and the degree of coverage is a reliable measure of the pollution load, especially of SO_2. The lichen cover was recorded on plots along an east-west transect (A) in 1995 and in 2004, and along a north-south transect (B) in 2004 (Fig. 4.11).

A large area was clearly an epiphytic lichen “desert”, and this area corresponded well with the most heavily polluted area surrounding the emission sources in Nikel and Zapoljarni (Fig. 4.11) (Bruteig 1984, Aamlid and Skogheim 2001). Plots N0, S03, S11 and RUS-2 had no epiphytic lichens on birch stems and were hence omitted from the figures (see Table 4.11). There was a clear increase, with increasing distance to the west, in the lichen cover to more than 20% of the stem circumference (PA). In the northern and southern directions the situation was the opposite; only the most remote plots had any lichen cover (N11 and RUS-0, respectively).

Table 4.11 Mean lichen cover as % of the total stem circumference, and distributed over the different aspects (N, E, S, and W). A: north-south transect, B: west-east transect. The data refer to 2004.

	Plot	Total	Total N	Total E	Total S	Total W
A	N11	0,62	0,20	0,17	0,08	0,17
	N06	0,00	0,00	0,00	0,00	0,00
	S03	0,00	0,00	0,00	0,00	0,00
	S05	0,00	0,00	0,00	0,00	0,00
	S10	6,41	1,60	1,79	0,62	2,40
	RUS-0	24,23	7,57	6,74	3,84	6,07
B	PA	20,64	6,56	4,46	2,06	7,56
	PB	7,56	2,41	1,81	1,16	2,46
	RUS-1	0,79	0,68	0,00	0,00	0,12
	RUS-2	0,00	0,00	0,00	0,00	0,00

A.



B

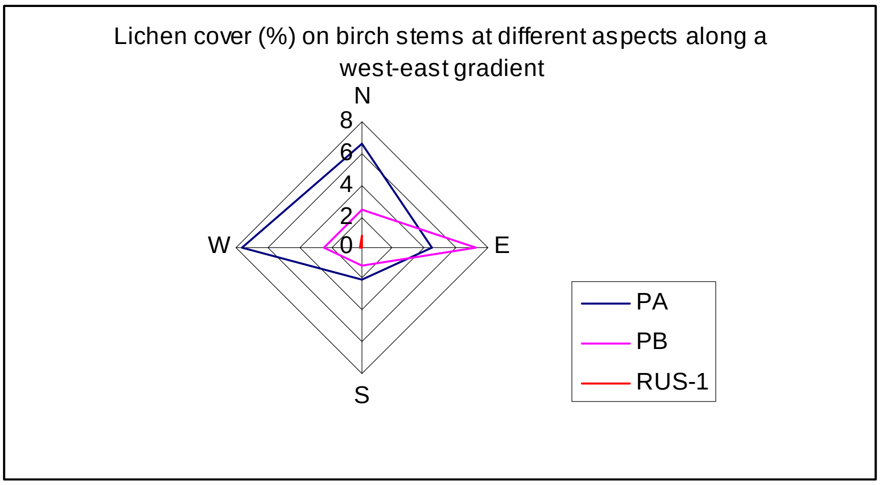


Figure 4.11 Mean lichen cover in % of total stem circumference, distributed over the different aspects (N, E, S, and W). A: north-south transect, B: west-east transect. The data refer to 2004.

The southern aspect of the stems had consistently the lowest lichen coverage. On the plots located to the north and north-west of Nikel, pollution may have contributed to this pattern (Aamlid et al. 2000). However, because this is also the case on the reference plot in the south (RUS-0), the irradiance level, species composition (cf. Aamlid and Skogheim 2001) or other natural environmental factors may be equally or more important factors determining the distribution of epiphytic lichens on the different aspects of the stem.

Comparison between the first (1995-98) and second (2004) survey of epiphytic lichen cover shows that lichens have recolonised to a substantial extent on the least polluted plots on the east-west transect (PA and PB) within a period of only a few years (Fig. 4.12, Table 4.12). The lichen cover may have decreased slightly on the most polluted plots close to the smelters, but these results should be treated with caution due to the low initial coverage. The coverage on the reference plot in Russia (RUS-0) has decreased slightly, but it is not likely to be affected by pollution owing to its remote position and the prevailing wind directions from south-southwest (Hagen et al. 2005). The recolonisation of epiphytic lichens found in this survey is in agreement with the reduction in emissions from Nikel and Zapolyarny that has taken place over the last 2-3 decades (Aamlid 2002).

Table 4.12 Percent coverage of lichens in 1995-98 and in 2004.

1995 PA	2004 PA	1995 PB	2004 PB	1995 RUS1	2004 RUS1	1998 RUS-2	2004 RUS-2	1998 RUS-0	2004 RUS-0
12,04	20,64	3,03	7,56	1,86	0,79	1,02	0,00	26,73	24,23

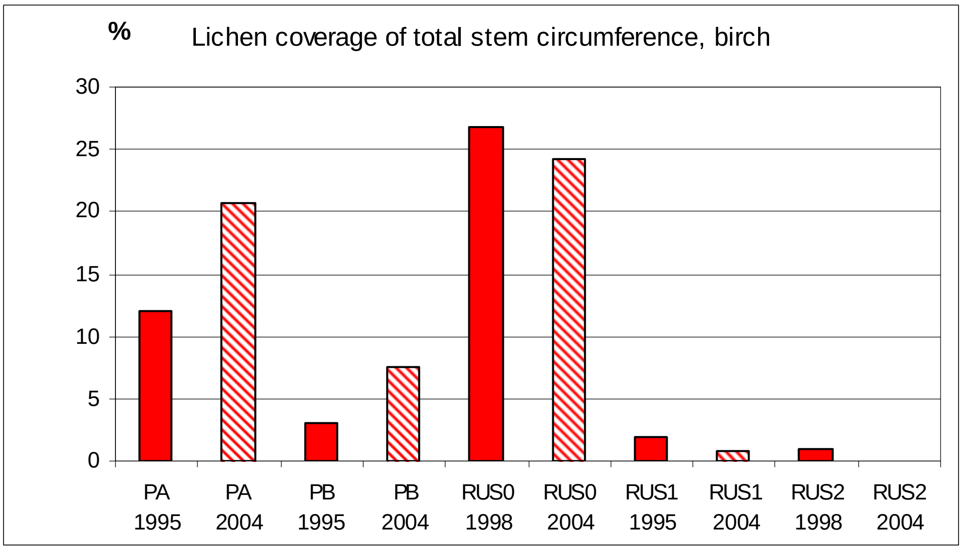


Figure 4.12 Percent coverage of all lichens of total stem circumference in 1995-98 and in 2004.

Pine stems

The epiphytic lichen cover was surveyed on 7 of the pine plots in Finland in 2005. The plots were species-poor with only five lichen species present. *Bryoria fuscescens*, and probably also a few specimens of other *Bryoria* species, e.g. *B. freemontii* (however, no yellow soralia visible), *B. simplicior* and *B. furcellata*, was by far the most common lichen (Fig. 4.13). It was recorded four times more frequently than the next lichen on the list, *Imshaugia aleurites*, which in tuen was recorded twice as frequently as the third lichen on the list, *Parmeliopsis ambigua*. *Hypogymnia physodes* was very rare, whereas *Melanelia olivacea* and *Buellia disciformis* were recorded only twice and once, respectively. The plots closest to Nikel had the lowest lichen abundance with less than 10% total cover, whereas the plots farther away from Nikel had up to 23.4 % total lichen cover (Fig. 4.14).

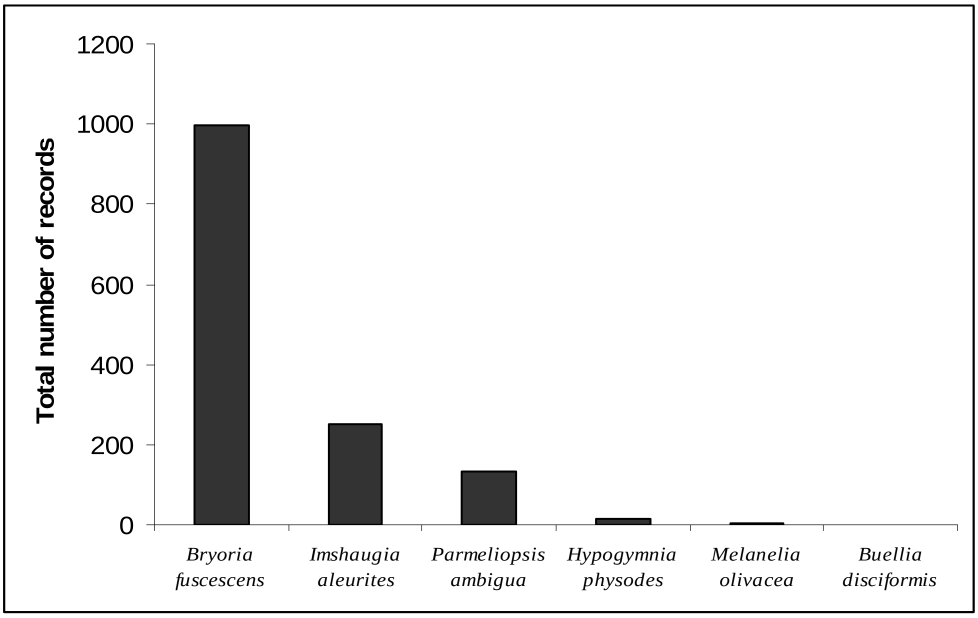


Figure 4.13 Number of records of lichens on the 7 plots in Finland.

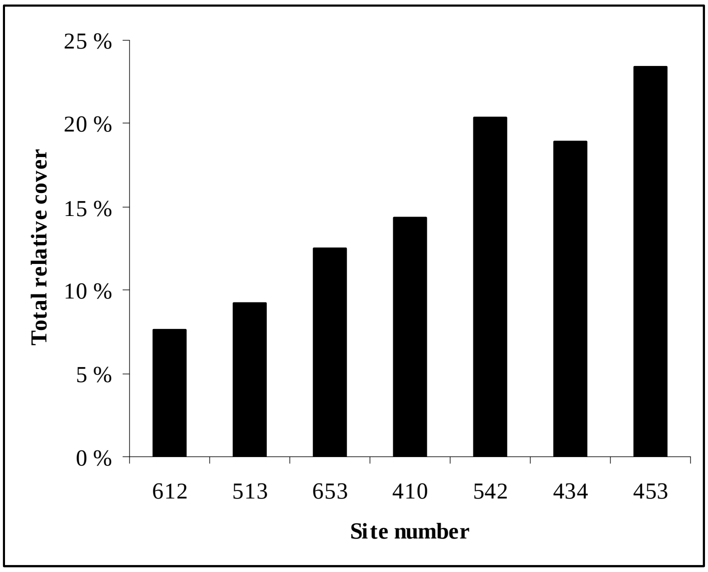


Figure 4.14 Total lichen cover on the 7 plots in Finland arranged according to distance from the Nikel smelters (site 612 nearest).

There was a strong relationship between the distance to Nikel and the lichen cover (Fig.4.15). The coefficient of determination (R^2) for the total lichen cover is 0.75, whereas for the W, N, S and E directions the values are 0.41, 0.45, 0.64 and 0.03, respectively. Hence, the E-facing side, which is the side facing Nikel, shows the strongest correlation with distance. For the S-facing side, the correlation is non-significant.

The N-facing sides of the tree trunks generally had the highest relative lichen cover, and the S-facing and E-facing sides usually had a very low cover or no cover at all (Fig. 4.15). At the plots closest to Nikel (plots 612 and 513), the E-facing sides of the trunks had no lichen cover, whereas on the three plots farthest away from Nikel, the lichen cover on the E-facing sides contributed 25-30% of the total lichen cover. The lichen cover on the N-facing side was as low as 29% on one plot at intermediate distance from Nikel, but the north-facing side on the two plots closest to Nikel had 68% and 82% of the total lichen cover. Some of the variation in the lichen cover was not related to the distance to Nikel, and was probably more attributable to differences in microclimate between the plots. This is supported by the low correlation for the S-facing side (Fig. 4.15E).

The survey on the 7 Finnish plots strongly indicated that the epiphytic vegetation is affected by air pollution from Nikel. Although none of the plots were totally lacking in lichens, there was a strong correlation between the distance to Nikel and the abundance of lichens. As this relationship does not seem to be correlated with any climatic gradient, pollutants from the smelter are the most likely factor accounting for the variation in distribution patterns. The effects of air pollution are further supported by the intra-trunk variation in lichen cover. The side of the trunk facing Nikel in general contributed only a small proportion of the total lichen cover, especially at the plots closest to Nikel. There was probably a larger amount of sulphur and heavy metals accumulated on this side of the trunk than on the other sides. The epiphytic lichen vegetation on the plots farthest away from Nikel did not show any clear response to emissions from Nikel. These plots had a relatively high lichen cover, and the E-facing side of the trunks actually had a higher lichen cover than the W-facing side. This indicates that the the accumulation of sulphur and heavy metals on the E-facing side is not greater than on the other sides. The higher lichen cover on the N-facing side is most certainly an effect of the microclimatic conditions. The N-facing side dries out much slower than the other sides, providing suitable moisture conditions for lichen growth. The opposite is the case on the S-facing side, which dries out faster and is therefore less suitable for lichen growth.

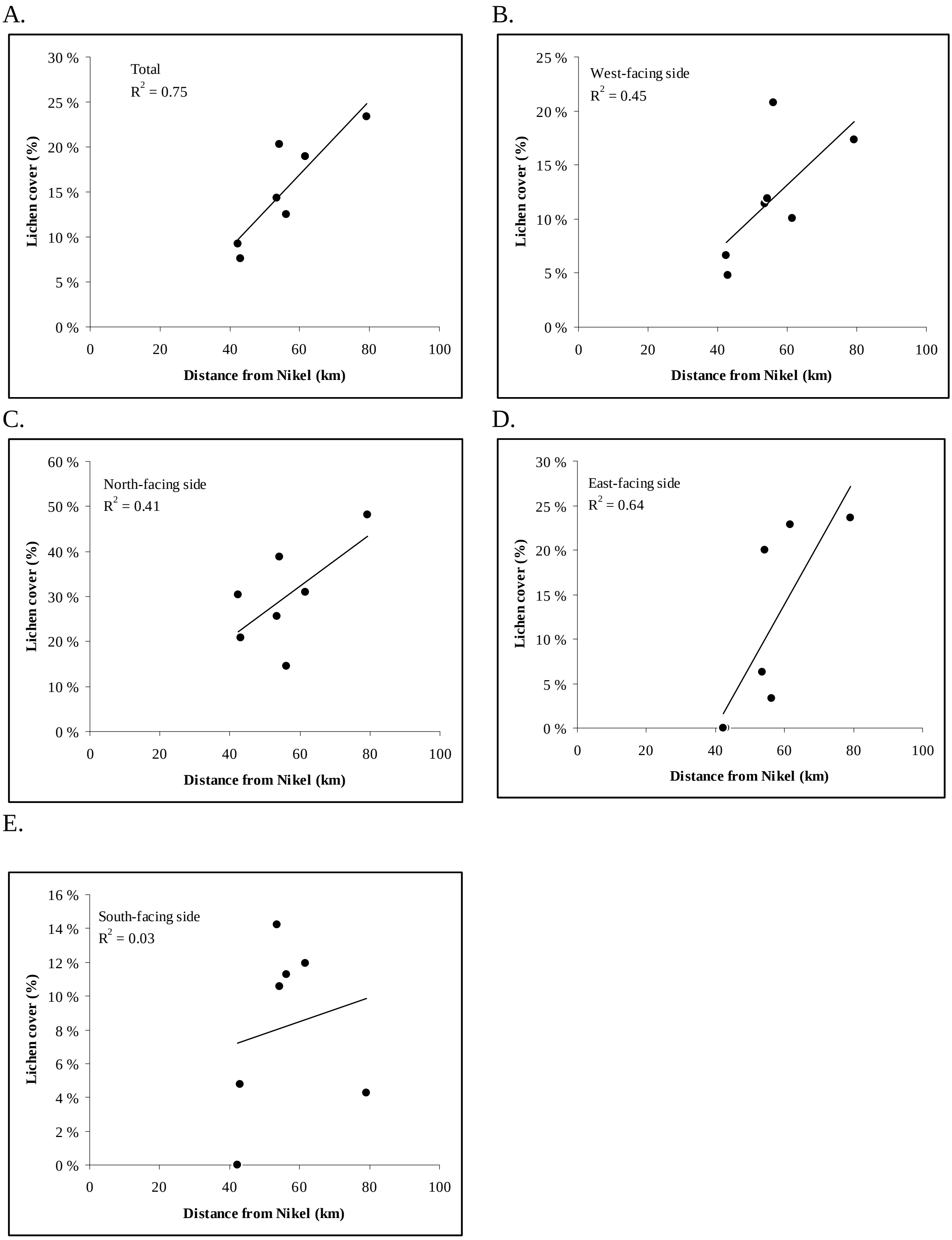


Figure 4.15 Lichen cover as a function of distance from the Nikel smelters. A. Total lichen cover (all directions), B. West-facing side of trunks, C. North-facing side, D. East-facing side of trunks, E. South-facing side of trunks.

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4.7. Photosynthetic efficiency

4.7.1. Estimation of plant vitality by means of fluorescence measurements on the INEP/NINA plots

Airborne pollutants can limit the growth of plants especially at high latitudes. Under such conditions the plants are growing at the limits of their distribution and at the extreme range of their habitat tolerance (Bliss l962). A sustained reduction in the efficiency of photosynthesis system II (PSII) has been reported in many species after exposure to unfavourable conditions (Osmond 1994, Demmig-Adams et al. 1998). Multiple environmental stresses lower the photosynthetic rate and increase the degree to which the absorbed light energy can be excessive and potentially damaging to PSII. The lowered photosynthetic efficiency (Fv/Fm) of PSII in stressed plants is inversely related to the energy release from the conversion states in the carotenoids of the xanthophyll cycle. This cycle, found to be present in all the higher plant species (ca. 30) investigated so far, safely dissipates the potentially destructive excess energy (for a review, see Demmig-Adams and Adams l996). This protective process, termed “photoinhibition” (Demmig- Adams et al. l998; Krause l994) or “photoinhibition of PSII” (Osmond l994), can be quantified on the basis of the ratio of the variable to the maximal chlorophyll fluorescence (Fv/Fm) (Kitajima and Butler l975). Odasz-Albrigtsen et al. (2000) found that the photosynthetic efficiency in birch *(Betula pubescens)* and bilberry *(Vaccinium myrtillus*) was negatively correlated with the concentrations of Cu, Ni, and SO_4, derived from emissions from the Cu–Ni smelters, in birch and bilberry leaves. Measurement of fluorescence in these species was found to be a sensitive indicator of the impact of air-borne pollutants. However, as the measurements and analyses have so far only been performed in the Norwegian part of the region, we considered it important to evaluate the variation in the photosynthetic efficiency of plants growing along the relatively sharp deposition gradients running from Nikel.

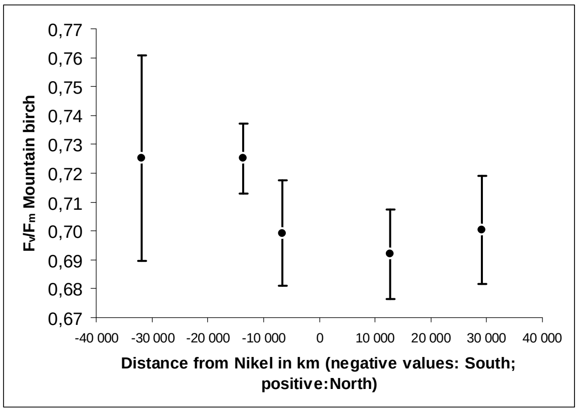
The photosynthetic efficiency (fv/fm index) of birch and bilberry, as well as the concentrations of airborne pollutants in the leaves of the same species, was measured at 17 plots along the northern, southern and western transects in 2000. In 2004, the same parameters were measured on the same species (same trees and cluster of plants) on 5 plots (S03, S05, S10, N06 and N11) along the northern and southern transects. In addition, photosynthetic efficiency was measured in lichens (mainly “reindeer lichens; *Cladonia* spp.) and in mosses *(Pleurozium schreberi* and *Hylocomiun splendens*), if present, on the same plots. The photosynthetic efficiency measurements were made with a Hansatech Plant Efficient Analyser. The Hansatech instrument was calibrated with the Plant Stress Meter used in the previous investigations in the area (Odasz-Albrigtsen et al. 2000). The number of trees, plants, mosses and lichens on each plot was 5, and 5 measurements were performed on each tree/plant/moss/lichen. The instrument is specifically designed for measuring plant vitality (chlorophyll fluorescence), expressed as the photosynthetic efficiency fv/fm. Chlorophyll fluorescence was measured in intact leaves on the lower branches of the birch trees, on leaves in the top of the bilberry plants, on the upper half of the thallus of the lichen clusters, and on the upper half of the green leafy moss clusters. Only green leaves were measured, and the leaves were selected at random. However, damaged or discoloured leaves were avoided. We compared the measurements from two years (2000 and 2004) in our study in order to assess whether there has been a change in vitality in the area. Statistical analysis (e.g. correlation analysis) was used to assess the suitability of fluorescence measurements in monitoring plant vitality in the study area.

The measurements of photosynthetic efficiency in 2004 showed that there was an increase in the vitality of birch and bilberry along the southern transect (S3, S5 and S10, negative values) from Nikel

(Table 4.13 and Fig. 4.15), as well as a smaller increase along the northern transect (N6 and N11, positive values) from Nikel, compared to the situation in 2000 (Yoccosz et al. 2001). Maximum values of fv/fm in both species were obtained on plot S10 on the southern transect, which is located 31 km from the Cu-Ni smelters.

Table 4.13 The photosynthetic efficiency expressed as mean fv/m for birch (B), bilberry (VM), reindeer lichens (Clad) and mosses (Moss).

Plot	Transect	Altitude, m	fv/fm, B	fv/fm, VM	fv/fm, Clad	fv/fm, Moss
N11	N	55	0,70	0,73	0,60	0,66
N06	N	105	0,69	0,70	0,00	0,71
S03	S	40	0,69	0,75	0,00	0,73
S05	S	150	0,73	0,77	0,51	0,66
S10	S	213	0,73	0,79	0,54	0,74



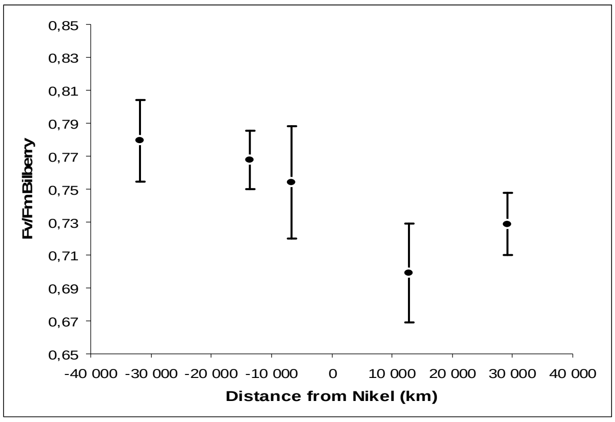


Figure 4.15 The vitality of mountain birch *(Betula pubescens* ssp. *czerepanovii)* and bilberry *(Vacciniun myrtillus)* expressed as the photosynthetic efficiency (fv/fm) along the north-south transects running through Nikel. Plots N11 (furthest to the right) and S10 (furthest to the left) are located 29 and 31 km from the Nikel smelters, respectively.

The vitality in 2004 was significantly better than that measured in 2000 (Table 4.14), indicating that growing conditions for the plants and trees have improved in the area since 2000 (Yoccosz et al. 2001).

Table 4.14 The photosynthetic efficiency expressed as mean fv/m for birch (B) and bilberry (VM). The values for plot S3 in 2000 are the means between S02 and S04, while the values for S05 are the means between S04 and S06, respectively.

Plot	Transect	Altitude, m	fv/fm, B 2000	fv/fm, B 2004	fv/fm, VM 2000	fv/fm, VM 2004
N12	N	45	0,76		0,73	
N11	N	55	0,69	0,70	0,69	0,73
N10	N	65	0,72		0,65	
Zapolyarniy						
N08	N	245	0,60		0,55	
N06	N	105	0,45	0,69	0,58	0,70
N04	N	110	0,61		0,69	
N03	N	65	0,55		0,54	
N01	N	75	0,55		0,58	
Nikel						
S02	N	46	0,54		0,52	
S03	S	40	0,54	0,69	0,52	0,75
S04	S	100	0,55		0,52	
S05	S	150	0,54	0,73	0,49	0,77
S06	S	225	0,54		0,47	
S09	S	268	0,56		0,59	
S10	S	213	0,52	0,73	0,61	0,79

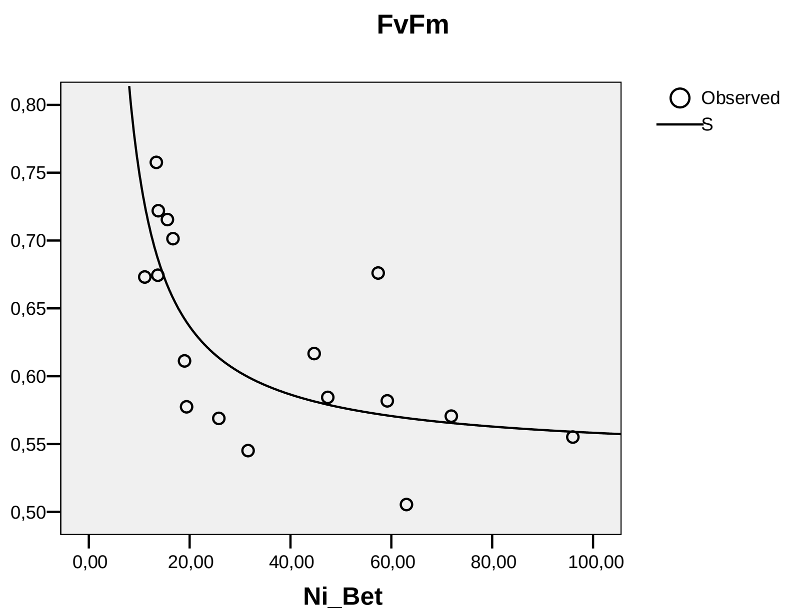


Figure 4.16 Relationship between the nickel concentration in birch leaves (ppm) and the photosynthetic efficiency (vitality) in birch trees expressed as fv/fm. Data are from the year 2000, and are based on 17 plots along the northern, southern and western transects running from Nikel.

4.7.2 Relationship between photosynthetic efficiency and Cu and Ni concentrations in birch leaves

The fluorescence measurements were analysed against different environmental parameters and concentrations of heavy metals in the soil and leaves using statistical analysis. A curvilinear, significant relationship was found between the Cu and Ni concentrations in birch leaves and the fv/fm measurements on 17 plots along the northern, southern and western transect on the basis of data from 2000 (Fig. 4.16). The relationship between the Cu and Ni concentrations in the organic layer at the same sites and the photosynthetic efficiency were weaker but significant.

These results show that the fluorescence method is suitable for the measurement of plant vitality on birch and bilberry, but not on lichens and mosses. Another procedure for lichens and mosses using total wet samples is recommended in the future (Bjerke 2006, oral communication). Similar conclusions were drawn in a similar study conducted in 1993 by Odasz-Albrigtsen et al. (2000). However, the SO_2 concentration in the ambient air, as well as environmental stress factors, also have a significant effect on plant vitality. The best plant species (indicator) for fluorescence measurements is considered to be bilberry, as concluded by Odasz-Albrigtsen (2000).

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4.8 Element concentrations in plants

4.8.1. Mosses

Terrestrial mosses have been widely used as biomonitors in regional heavy metal surveys. They are highly suitable heavy metal biomonitors because they obtain most of their nutrition from wet and dry deposition, and they also have several properties that promote the accumulation of heavy metals. The deposition of heavy metals (Cd, Co, Cr, Cu, Fe, Ni, Pb, Ti, V, Zn) and sulphur in the area affected by emissions from the Nikel smelters was investigated by collecting and analysing moss samples. The samples were collected in August 2004 from 16 plots located at distances ranging from 7–72 km from the smelter. The moss species collected on the Finnish plots (9 plots) were Hylocomium splendens and Pleurozium schreberi, and on the Norwegian plots (5) only Hylocomium schreberi and on the Russian plots (2) only Pleurozium schreberi. In cases where both moss species were obtained from the same plot, only the concentrations in Hylocomium splendens are presented in this report. No moss samples were obtained from the background plot (RUS0).

Metal concentrations in mosses

The concentrations of most of the heavy metals, especially Ni and Cu, were high at a distance of 10 km from the emission source. The Ni concentration on the plot nearest to the smelter was 517 mg/kg and the Cu concentration 290 mg/kg (Table 4.15). The Co (14.5 mg/kg), Cd (0.63 mg/kg), Cr (6.2 mg/kg), Fe (1638 mg/kg) and Pb (17.5 mg/kg) concentrations were also relatively high near the smelter, whereas the V, Zn and Ti concentrations were not noticeably elevated. The heavy metal concentrations clearly decreased at distances greater than 25 – 30 km from the smelter The heavy metal concentrations on the Finnish plots were relatively low. The Ni, Cu and Co concentrations decreased the most regularly with increasing distance from the smelter (Fig. 4.17). The Pb, Cd and Cr concentrations were relatively high near the emission source, but they decreased relatively sharply already at a distance 10 km. There was no decreasing trend in the Mn and Ti concentrations.

Table 4.15 Heavy metal and sulphur concentrations in mosses (mean, median, standard deviation, minimum, maximum; correlation, F-value and statistical significance) in relation to distance from the smelters.

	Cd	Co	Cr	Cu	Fe	Mn	Ni	Pb	Ti*	V*	Zn	S
Mean	0.17	3.02	1.54	57,0	509	522	93,8	4,48	27,7	1,07	34,3	976
Median	0,10	0,85	1,09	18,9	291	467	26,7	3,05	19,1	0,90	27,5	890
Stand dev	0,14	3,98	1,33	76,9	479	235	135,8	3,86	26,5	0,45	15,6	292
Minimum	0,06	0,37	0,83	8,4	136	236	9,7	1,80	4,0	0,62	19,4	657
Maximum	0,63	14,46	6,21	290,2	1638	1212	516,6	17,54	106,0	2,04	77,2	1824
Correlation	-	-	-	-	-	-	-	-	-	-	-	-
	0,722	0,811	0,502	0,776	0,832	0,196	0,763	0,650			0,661	0,794
F value	14,16	24,94	4,39	19,68	29,32	0,52	18,13	9,53	-	-	10,11	22,22
P	0,002	0,000	0,056	0,001	0,000	0,483	0,001	0,009	-	-	0,007	0,000
Median[1]	0,09	-	0,69	4,26	365	-	1,11	2,70	-	1,36	29,4	-
Median[2]	0,12	-	1,25	3,96	259	-	1,83	3,37	-	1,45	28,8	-

Median[1] = Concentrations in mosses in Norway 2000 (Buse et al. 2003, Steinnes et al. 2001)
Median[2] = Concentrations in mosses in Finland 2000 (Buse et al. 2003, Poikolainen et al. 2004)
* No concentration available for plot RUS1

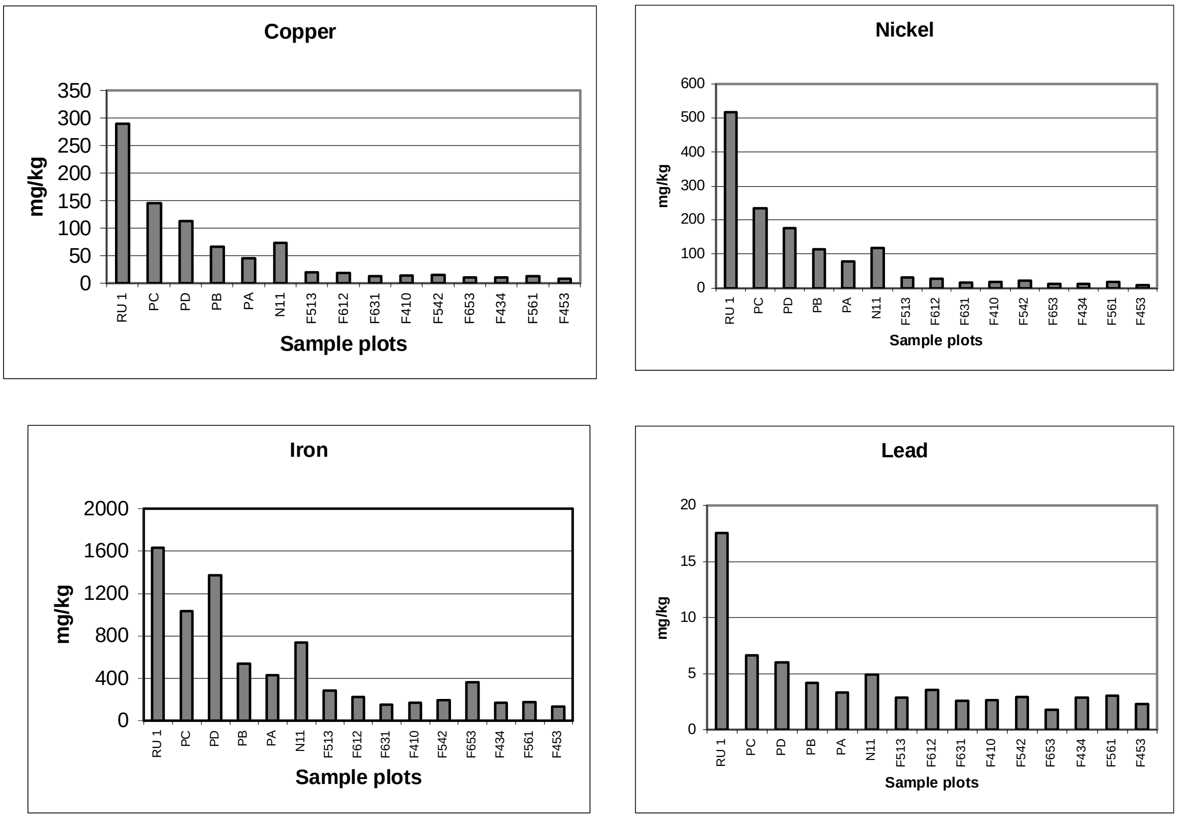

Figure 4.17 Concentration of copper, nickel, iron and lead in mosses on the plots.

The degree and extent to which emissions are spread depends on the type of emission source, the composition of the emissions and the weather conditions. In general, heavy metals are attached to the emitted particles, and the majority of the heavy metal emissions are deposited close to the source. According to the concentrations in the mosses, most of the heavy metals emitted from the Nikel smelters are deposited on the ground and vegetation cover at distances of less than 10 km. The heavy metal concentrations, apart from those of Ni and Cu, on the Finnish plots were at almost the same level as a the median values in the nation-wide surveys in 2000 on mosses in Norway (Steinnes et al. 2001) and in Finland (Poikolainen et al. 2004). In other words, they were close to the so-called background levels. However, the Ni concentrations on the Finnish plots were 5–10 and the Cu concentrations 2–3 times higher than the median value in the Norwegian and Finnish surveys in 2000. Similar results have also been reported in other surveys on heavy metal concentrations and damage to a number of plant species in the surroundings of the Nikel smelter (Gytarsky et al. 1994, Tikkanen & Niemelä 1995, Aamlid et al. 2000)

The Ni and Cu concentrations in mosses in 2004 were clearly higher than those reported in the 1990´s on the plots located nearest to the smelter (RUS1), and also slightly higher on some of the Norwegian plots (PC, PD) (Aamlid et al. 2000). The Ni concentration in mosses also increased in NW Finland between 1985 to 2000, but the Cu concentration remained relatively constant between during the period 1985 – 2000 (Poikolainen et al. 2004). The year-to-year variation in Cu and Ni concentrations are mainly due the weather conditions and the emission levels. Reimann et al. (1999) found, in their heavy metal studies on the Kola Peninsula, that the concentrations of many of the elements in mosses are probably more closely related to the chemical composition of rainwater than to the annual deposition level.

The heavy metal concentrations in mosses do not directly reflect the total deposition of heavy metals. There are differences in the accumulation of heavy metals in mosses, and the concentrations in mosses are also affected by factors other than atmospheric pollution. Factors affecting the concentrations in mosses, especially in the surroundings of the Nikel smelter, are the weather conditions, the amount of soil dust in the air, and the condition of the mosses. Soil dust has been shown to have a significant effect on the Fe, Ti and Cr concentrations in mosses. However, the Cu and Ni concentrations in mosses are especially good indicators of the spread of Cu and Ni emissions in the surroundings of the Nikel smelter.

Sulphur concentration in mosses

The sulphur concentration in mosses near the smelter was very high (1824 mg/kg). The concentrations on the Norwegian plots ranged from 1010 mg/kg to 1233 mg/kg, and on the Finnish plots from 709 mg/kg to 896 mg/kg. Although the decrease in the sulphur concentration was significantly related to the increasing distance from the smelter (Table 4.15), the sulphur concentration did not decrease as clearly as the Ni and Cu concentrations (Fig. 4.18).

Mosses are not considered to be especially good biomonitors of sulphur deposition, although sulphur concentrations have been found to reach high levels close to emission sources and to correspondingly decrease with increasing distance from emission sources (Mäkinen 1994, Äyräs et al. 1997). The results of this survey support these earlier findings. The reason why mosses are relatively poor bioindicators may be that sulphur at high concentrations damages the mosses and alters their accumulation capacity. There is also natural variation in the sulphur concentration of plants in the study area, which is due e.g. to the maritime climate (Kashulina et al. 2003). However, the sulphur concentrations in mosses indicate elevated sulphur deposition in the study area, and sulphur emissions from the smelter are clearly distributed over a larger area than the heavy metal emissions. The sulphur concentrations in mosses were now higher than in 1994 on the plots nearest to the smelter (RUS1), and slightly lower on the Norwegian plots (Aamlid et al. 2000).

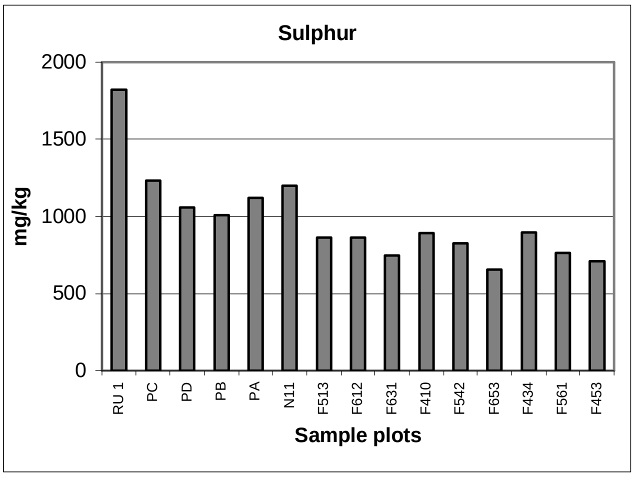

Figure 4.18 Sulphur concentration in mosses on the sample plots.

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4.8.2. Other vegetation

<u>Bilberry leaves (*Vaccinium myrtillus*), wavy hair-grass (*Deschampsia flexuosa*) and reindeer lichen (*Cladonia rangiferina*)</u>

In general, there was a clear gradient in the Cu and Ni concentrations in all three species, with the highest values on the plots close to the smelters (Table 4.16). In bilberry leaves and wavy hair-grass, the highest Cu and Ni concentrations occurred on the plot to the north of the emission source (N06) and not on the plots close to the smelter (e.g. RUS-1), and there were also extremely high Ni concentrations in wavy hair-grass on the Russian reference plot (RUS-0). There was no clear pattern for the Zn concentrations, although the highest Zn concentrations in wavy hair-grass occurred in the affected area (e.g. PA, PB) rather than in the reference area (Finland).

Reindeer lichens are unique in their ability to accumulate heavy metals over a period of several years. This phenomenon was reflected in the results of this survey, the Cu and Ni concentrations being about 20 times higher than those in the vascular plants on the most polluted plots. The Cu and Ni concentrations in reindeer lichen were strongly related to the distance from the emission source, the concentrations consistently decreasing on moving to the S, W and N from the emission source. The Co, Cr and Pb concentrations were also strongly elevated on the plots close to the smelters. As for vascular plants, there was no clear gradient in the Zn concentrations in reindeer lichens, although the highest levels occurred in the most contaminated area (N05, N06).

When the Cu and Ni concentrations in reindeer lichen (*Cladonia rangiferina*) in the present survey are compared with the concentrations in *C. stellaris* collected on the same plots 8 years earlier (Aamlid et al. 2000), it is clear that the concentrations of Cu and Ni have increased considerably during the 8-year period. The increase in the Ni concentration on plot PD was two-fold. The gradient in the heavy metal concentrations (PA-PD, RUS 1-RUS-0) also resembles that reported by Aamlid et al (2000). However, the fact that different species of reindeer lichen were sampled in the two surveys makes this comparison somewhat uncertain.

Table 4.16 Heavy metal concentrations (mg/kg) in bilberry leaves (*Vaccinium myrtillus*), wavy hair-grass (*Deschampsia flexuosa*) and reindeer lichen (*Cladonia rangiferina*).

Plant species	Metal	FI-4	FI-5	FI-6	PA	PB	PC	PD	RUS-1	RUS-0	N11	N06	S05
Vaccinium	Cu	5.01	5.35	6.23	6.23	5.66	9.28	6.55	11.0	6.14	6.86	17.3	6.71
myrtillus	Ni	1.73	1.68	1.88	6.99	5.64	16.0	9.92	20.0	4.87	6.69	37.9	13.4
	Zn	11.3	11.1	10.5	11.8	10.7	9.02	8.89	7.15	12.7	11.8	8.11	9.22
Deschampsia	Cu	3.52	3.65	3.34	3.05	3.75	5.02	3.62	7.75	8.83	3.56	7.57	3.72
flexuosa	Ni	3.33	3.65	3.58	7.75	9.22	12.8	6.63	10.6	22.7	6.69	26.9	10.5
	Zn	16.0	17.2	11.7	20.5	20.0	19.8	13.3	18.0	16.1	14.7	13.9	13.2
Cladonia	Co	0.43	0.61	0.44	1.94	2.53	6.31	3.89	10.5	1.12	2.30		7.63
rangiferina	Cr	0.62	0.61	0.52	1.09	1.09	1.51	1.09	3.09	0.64	1.09		3.10
	Cu	11.5	13.2	10.8	34.4	48.2	111	74.3	147	13.8	40.7		98.3
	Ni	12.7	18.3	13.6	56.3	76.3	172	110	232	24.0	63.3		125
	Pb	1.61	1.92	2.21	1.45	2.28	3.94	2.69	5.78	1.41	2.07		8.03
	Zn	19.1	17.6	14.8	24.1	19.7	19.0	18.2	24.2	14.8	26.7		26.0

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4.9. Birds

The species composition of hole nesting passerines and information about the reproductive success of the pied flycatcher (*Ficedula hypoleuca*) were recorded in nesting boxes along the pollution gradient running to the west of the Nikel smelters. Each plot had about 40 bird boxes located along a double line, 50 m apart with a distance of 30 meters between the boxes in the line. The tail feathers of both young and adults were sampled for chemical analysis.

Concentrations of metals in feathers

In general, the concentrations of heavy metals in the feathers of young pied flycatchers are much lower than those in adults. The concentrations in adults showed a clear decreasing trend with increasing distance from the smelters. The trend was significantly lower only for the adults (Fig. 4.19, Table 4.17).

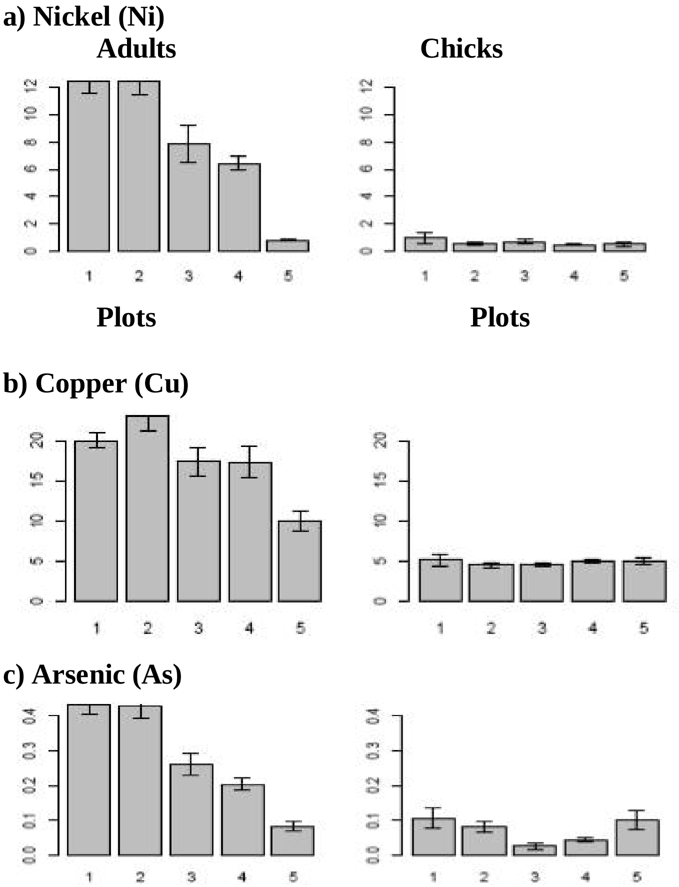

Figure 4.19 The concentration of nickel, copper and arsenic in the tail feathers of the pied flycather at various distances from the Nikel smelters. Sample plots 1 to 4 are at distances of 5, 8, 13 and 22 km, respectively, while plot 5 is a reference area in Lakselvdalen outside the city of Tromsø more than 700 km from the Nikel smelters. (Note different scale on the vertical axes). Plots 1 to 4 refer to the monitoring plots PC,PD,PB and PA, respectively.

Effects of metal concentration on breeding birds

The pied flycather accounted for more than 85 % of the total number of birds breeding in the nest boxes on all the plots. Other species occupying the boxes were the great tit (*Parus major*), the Siberian tit (*Parus cinctus*) (not on the reference plot) and the red start (*Phoenicurus phoenicurus*). There was little variation in the breeding density between the plots (except for the plots on the Russian side, which had a much lower density). Furthermore, parameters such as egg laying date and clutch size were relatively similar between the plots. However, the body mass of nestlings was lower on plots where the parents had the highest metal concentrations (Fig. 4.20). A low body mass at fledgling may severely reduce their chances of survival and becoming recruited in the earlier documented flycatcher population.

Adult females showed increased fluctuating asymmetry (FA) in tarsus length in the most polluted areas (Fig. 4.21). This suggests that the birds may be subjected to stress in the area. An increase in FA is a biologically early warning sign of developmental instability expressed by many animals under various types of environmental stress.

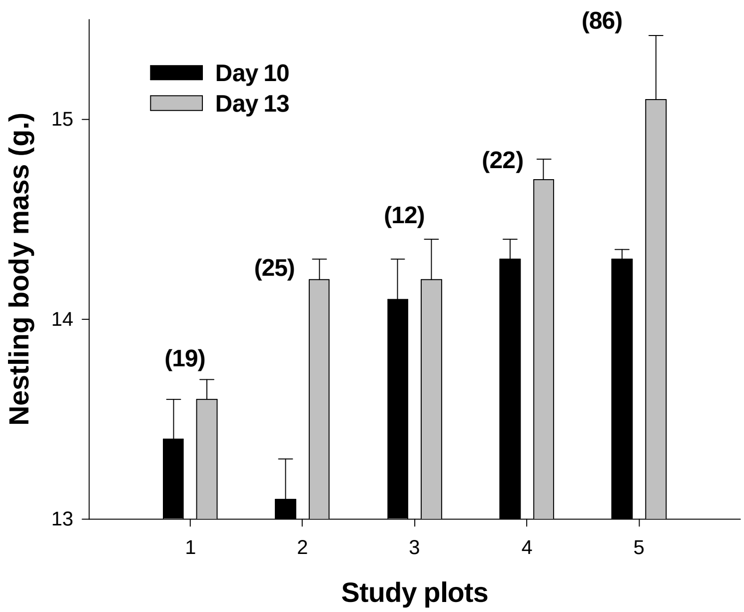

Figure 4.20. The body mass of pied flycatcher nestlings at different distances from the Nikel smelters. The data refer to chicks 10 day after hatching and at about fledging age (day 13). See Fig. 4.19 for explanation of plot number.

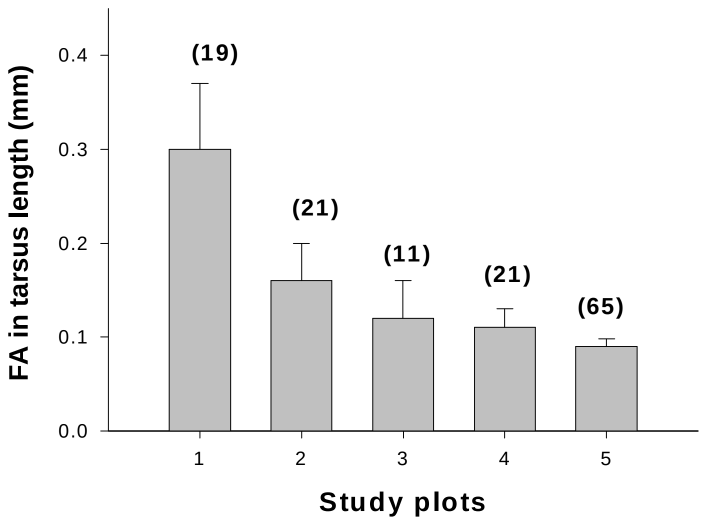

Figure 4.20 Fluctuating asymmetry (FA) in tarsus length of adult female pied flycatchers at different distances from the Nikel smelter. See Fig. 4.19 for explanation of plot number.

Table.4.17. Concentrations of heavy metals in tail feathers (μg/g dry weight) of the pied flycatcher at different distances from the Nikel smelters. Plots 1 to 4 are located at distances of 5, 8, 13 and 22 km, respectivel, while Lakselvdalen is a reference area close to the city of Tromsø more than 700 km to the west of the Nikel smelters. Juv = juvenile, Ad = adult.

Plot	1				2				3				4				Lakselvdalen			
Metal	Juv (n = 4)		Ad (n = 15)		Juv (n = 11)		Ad (n = 20)		Juv (n = 6)		Ad (n = 7)		Juv (n = 7)		Ad (n = 11)		Juv (n = 12)		Ad (n = 13)	
	Avg	*Std.e*	*Avg*	*Std.e*	*Avg*	*Std.e*	*Avg*	*Std.e*	*Avg*	*Std.e*	*Avg*	*Std.e*	*Avg*	*Std.e*	*Avg*	*Std.e*	*Avg*	*Std.e*	*Avg*	*Std.e*
Cd *111*	0,008	0,007	0,092	0,008	0,007	0,003	0,517	0,387	0,009	0,002	0,104	0,013	0,010	0,002	0,133	0,023	0,013	0,005	0,104	0,008
Cd *114*	0,011	0,006	0,097	0,007	0,007	0,003	0,486	0,360	0,006	0,002	0,098	0,011	0,009	0,002	0,130	0,022	0,017	0,004	0,104	0,010
Hg	0,585	0,117	0,860	0,117	0,597	0,067	1,70	0,182	0,691	0,040	1,63	0,520	0,513	0,099	1,40	0,194	0,346	0,017	0,889	0,100
Pb	0,242	0,143	2,06	0,279	0,056	0,014	2,46	0,324	0,158	0,042	2,12	0,242	0,107	0,025	1,86	0,259	0,174	0,025	2,05	0,203
Al	13,8	6,71	92,0	11,3	5,50	1,20	130	11,6	18,3	5,53	125	25,7	17,9	5,22	128	21,5	26,0	7,51	157	37,5
Ca	617	42,4	791	153	788	36,3	1237	106	747	28,4	734	86,6	698	30,1	658	64,9	748	78,0	1398	109
Cr	0,115	0,023	0,649	0,109	0,179	0,039	0,786	0,076	0,213	0,033	0,549	0,055	0,122	0,010	0,572	0,077	0,265	0,061	0,643	0,062
Fe *56*	2,34	1,41	18,22	2,48	1,36	0,222	22,8	1,73	2,98	0,725	20,2	4,14	2,41	0,496	25,4	2,28	14,1	5,49	41,9	4,96
Fe *57*	41,5	11,8	145	13,3	27,5	1,61	188	41,8	52,6	10,7	144	24,5	33,9	3,73	149	23,2	59,5	14,3	153	26,2
Co	44,3	13,3	146	14,0	28,6	1,49	192	42,0	51,2	10,3	141	24,5	33,1	3,48	152	24,1	57,1	13,8	145	25,0
Ni	0,040	0,014	0,631	0,098	0,028	0,005	0,712	0,062	0,044	0,008	0,566	0,105	0,028	0,003	0,495	0,059	0,074	0,023	0,323	0,036
Cu	0,988	0,381	12,4	0,799	0,568	0,106	12,4	1,02	0,724	0,170	7,82	1,31	0,499	0,056	6,43	0,512	0,521	0,146	0,850	0,070
Zn *67*	5,18	0,771	20,1	0,976	4,52	0,332	23,0	1,79	4,65	0,209	17,4	1,69	5,02	0,302	17,3	1,98	4,97	0,441	10,0	1,16
As	161	6,90	79,6	6,12	137	4,49	84,9	8,23	158	5,46	83,1	11,5	164	4,20	89,5	7,71	167	7,95	83,0	7,51
Se	0,106	0,029	0,431	0,024	0,082	0,015	0,427	0,033	0,027	0,009	0,262	0,030	0,045	0,006	0,205	0,019	0,102	0,026	0,084	0,014

4.10. Satellite imagery

Monitoring the vegetation in the study area using satellite imagery in 7 separate years during the period 1973 – 1999 (Fig. 4.22) clearly indicated that major changes have occurred, especially in the lichen (epigeic) dominated vegetation cover, since 1973 when these vegetation formations were dominating (Tømmervik et al. 2003). The satellite data were analyzed and correlated with chlorophyll fluorescence measurements (photosynthetic efficiency), and significant positive relationships were found between the photosynthetic efficiency in species common in the mixed forest vegetation and the NDVI (Odasz-Albrigtsen et al. 2000). We found a significant negative relationship ($r = -0.94$, $p = 0.001$) between the extent of the area of mixed forests with a lichen cover and SO_2 emissions during the period. The area of the category "industrial barrens" had a significant negative relationship ($r = -0.95$, $p = 0.001$) with SO_2 emissions during the same period (Tømmervik et al. 2003). The overall accuracy of the different maps produced in the period 1973-199 was 75–83%.

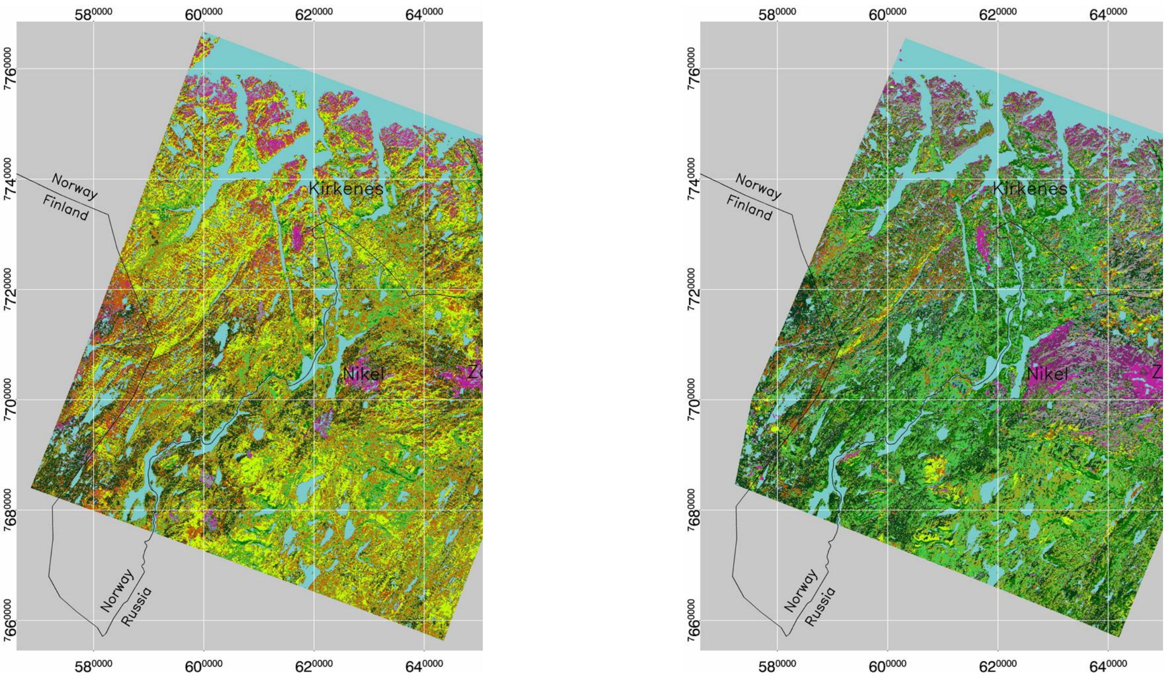

Figure 4.22 Land cover maps based on Landsat imagery of the study area. Damaged areas are shown in red to violet colour, abd lichen-dominated forests and alpine heaths are yellow to green. The map shows the situations in 1973 and in 1999.

Satellite monitoring of the study area continued with an assessment of a Landsat scene from 26th July 2004. The data from 2004 were compared with previous satellite images taken during the period 1973 – 1999 (Tømmervik et al. 2003) in order to reveal changes in the vegetation at the landscape and regional levels. The coverage of lichen was at its lowest (due to air pollution) in 1992, with a subsequently increase from 1994 to 2004.

Using the low resolution satellites like NOAA-AVHRR and MODIS on the TERRA satellite, the biomass (Fig. 4.23) can be monitored on a daily and an annual basis using the Normalized Difference Vegetation Index – NDVI (Tømmervik et al. 2005), as well as phenological events and the length of the growing season (Fig. 4.24) (Høgda et al. 2006 in print, Karlsen et al. 2006). The length of the growing season clearly increased during the period 1982 - 2002 in the immediate surroundings of the Nikel smelters. The NOAA-AVHRR and the MODIS data are available free of charge for the scientific community, and are assessed through phenological monitoring projects (Phenoclim and NorSEN) led by NORUT with co-partners in Norway (NINA and Svanhovd Environmental Center), Russia (Kirovsk Botanical Garden, Pasvik Zapnovednik) and Finland (FMI and METLA).

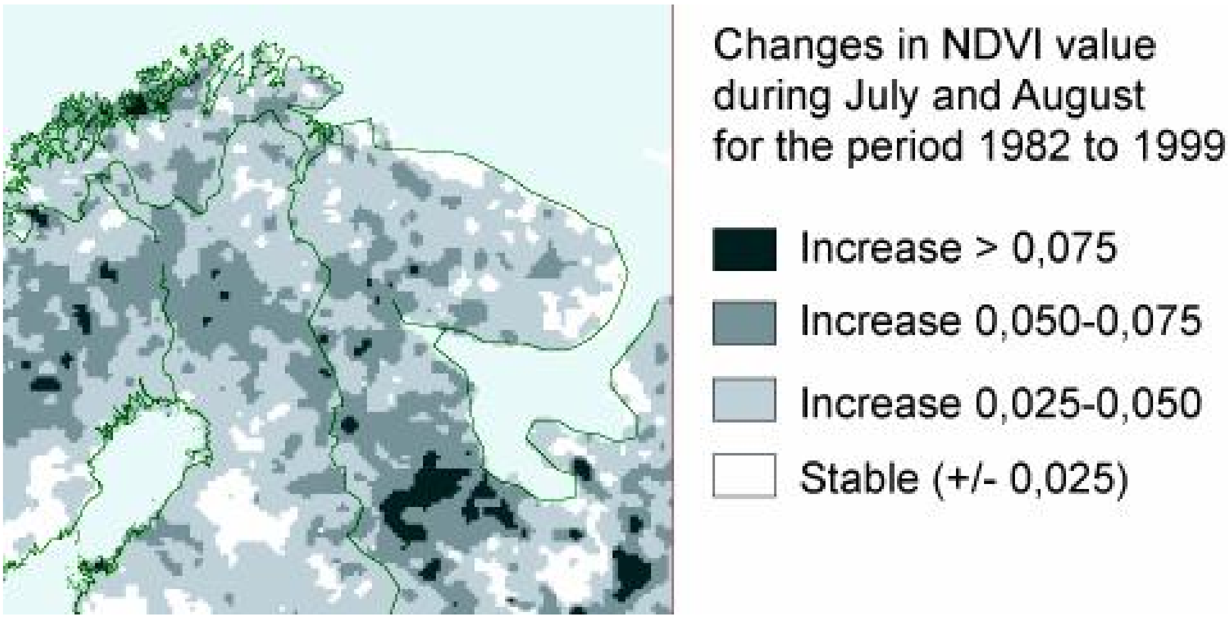

Figure 4.23 Changes in the NDVI values in July and August during the period 1982 - 1999 in Fennoscandia monitored by the NOAA-AVHRR satellites (NASA GIMMS data set). The NDVI value express the status of the vegetation (vitality) as well as the biomass. Source: Tømmervik et al. 2005.

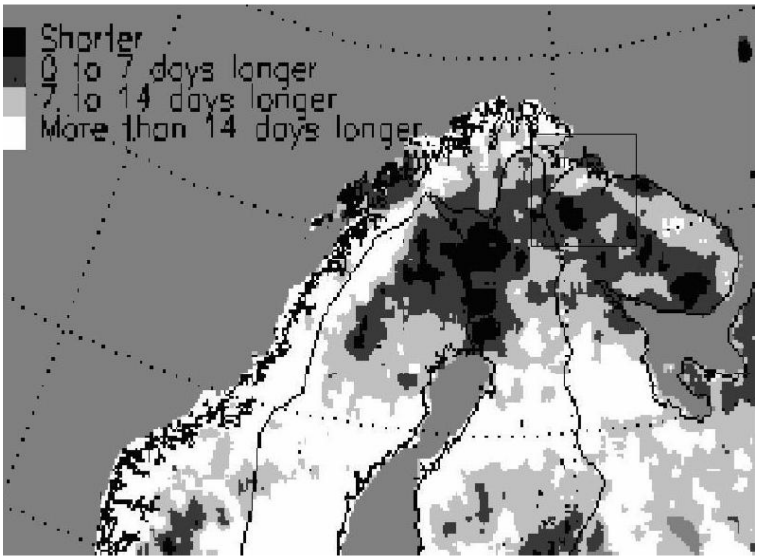

Figure 4.24 The spatial variation in the length of the growing season (1982 -2002) in Fennoscandia monitored by the NOAA-AVHRR satellites (NASA GIMMS data set).

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WWW-sites:

Phenoclim: http://projects.itek.norut.no/phenology/no/
NorSEN: http://norsen.fmi.fi/

5. Conclusions concerning the current state of the terrestrial ecosystems

There are signs of a slight recovery in the condition of terrestrial ecosystems in the area around the emission source, e.g. the reappearance of pioneer species of bryophytes and lichens on a number of the Russian plots, and the marked recolonization of epiphytic lichens on the least polluted plots along the transect running to the west of the smelter. Satellite imagery indicates that there has been an increase in lichen coverage in the area from 1994 to 2004. These plants are sensitive indicators of pollution, especially SO_2. Furthermore there has been an increase in the vitality of birch and bilberry (measured as photosynthetic efficiency) along the transect running to the south of the smelter, as well as a smaller increase along the transect running to the north. In contrast, the accumulation of heavy metals (especially Ni) in mosses has increased during the past 15 years, and the concentrations of Cu and Ni in edible berries currently still exceed the maximum levels allowed in foodstuffs for human consumption. The soil (litter and humus layers) close to the smelter contains extremely high concentrations of a wide range of heavy metals, representing accumulation over the lifetime of the smelters. Although a relatively high proportion of the metals are in an immobilized form, the concentrations of plant-available metals are still excessively high. The soil in the immediate vicinity of the smelter is not suffering from soil acidification, despite the continued relatively high level of SO_2 emissions. This is due to the abundant occurrence of basic types of bedrock in the area, as well as to the relatively low rate of conversion of SO_2 to sulphuric acid in the relatively dry, cold Arctic climate.

Overall, the results suggest that there has been a decrease in the emissions of SO_2 in recent years, but that this has not been paralleled by a corresponding decrease in heavy metal emissions.