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The ecological state of the ecosystems in the border areas between Norway and Russia

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Six sites for forest ecosystem monitoring were established to perform a long-term study of effects of air pollution on pine forest ecosystems along a pollution gradient in the border areas between Norway and Russia. The main pollution source is a nickel smelter. Several methods and analyses were used to investigate different compartments of this northern boreal forest ecosystem. The differences in ecological condition and diversity observed among the research sites are probably due to the air pollution load in the area. The elevated concentrations of Ni and Cu detected in plant tissues, the reduced lichen vegetation on stems and on the forest floor, and the reduced or absent moss vegetation are the most obvious impacts in the investigated area.

Introduction

Long-term influence of sulphur dioxide (SO_2) has resulted in visible environmental damage in the border area between Russia and Norway. The emission sources are mainly the metal smelters in Nikel and Zapolyarnyy on the Kola Peninsula (Fig. 1). Similar conditions are found elsewhere on the Kola Peninsula (Alexeyev 1995, Rigina and Kozlov 2000, Vassilieva *et al.* 2000).

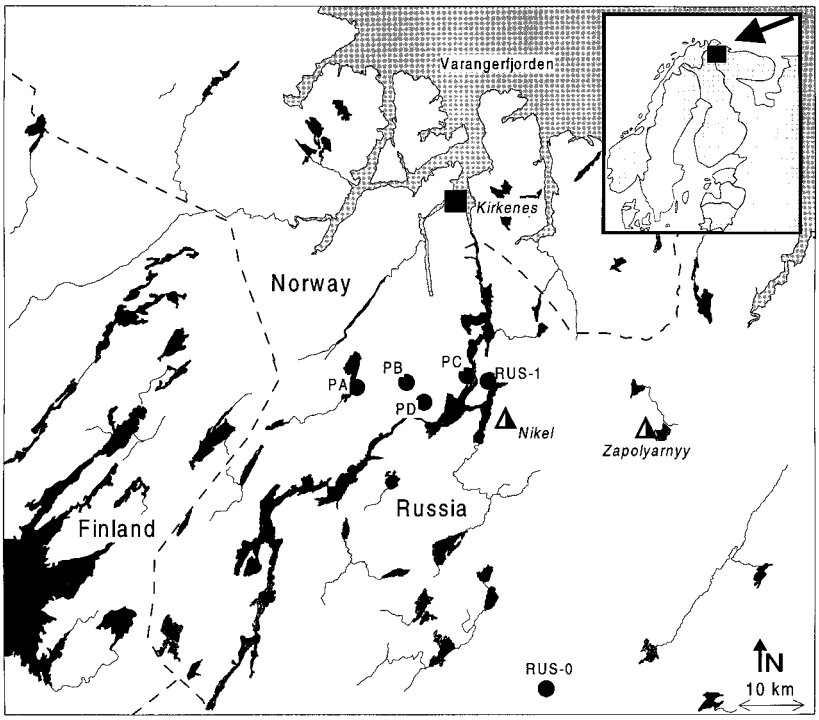

Fig. 1. Location of the monitored sites.

The critical level of sulphur dioxide for sensitive ecosystem components was exceeded on more than 3 200 km^2 of Russian and Norwegian territory. A considerably larger area was probably influenced by air pollution because raised pollutant levels could be traced by chemical analysis of plants and soils sampled from far outside the area in which critical levels were exceeded (Aamlid *et al*. 1995, Tømmervik *et al*. 1995, Gytarsky *et al*. 1997).

Visible injuries to vegetation caused by SO_2 have been observed in the forest next to the Russian border. Symptoms were mainly recognised on pine (*Pinus sylvestris*) and birch (*Betula pubescens*) which are the dominant tree species in the region. However, injuries were observed on other plants too, e.g. *Betula nana* and *Vaccinium myrtillus* (Aamlid 1993). The species composition of the ground vegetation in the forest may be influenced by air pollution (Aarrestad and Aamlid 1999). Investigations of the epiphytic lichen vegetation (Aamlid 1992, Vassilieva *et al*. 1995, and I. Bruteig pers. comm.) showed that epiphytic lichens are severely influenced over large areas.

In 1993/1995 a set of six sites for forest ecosystem monitoring was established for a long-term study of pine forest ecosystems along a pollution gradient in the Norwegian–Russian border area. The main purpose of the present work is to describe the ecological state of these pine forest ecosystems, where the exceedance of the critical level for terrestrial biota has probably occurred for several decades. Several methods and analyses were used to investigate different components of this northern boreal forest ecosystem.

Material and methods

Geographical location

The research area is situated in the border areas between Norway and Russia (77°N, 30°E) where air pollution from nickel smelters on the Kola Peninsula has been significant for decades. Industrial emissions in Nikel and Zapolyarnyy alone were estimated at 270 000 tonnes of sulphur dioxide in 1989, and 11% less in 1990 (Sivertsen *et al*. 1994, Chisov 1995). During the research period, the emissions may have varied around the 1990 level. In addition to SO_2, Ni and Cu are emitted in large amounts. The five monitoring sites

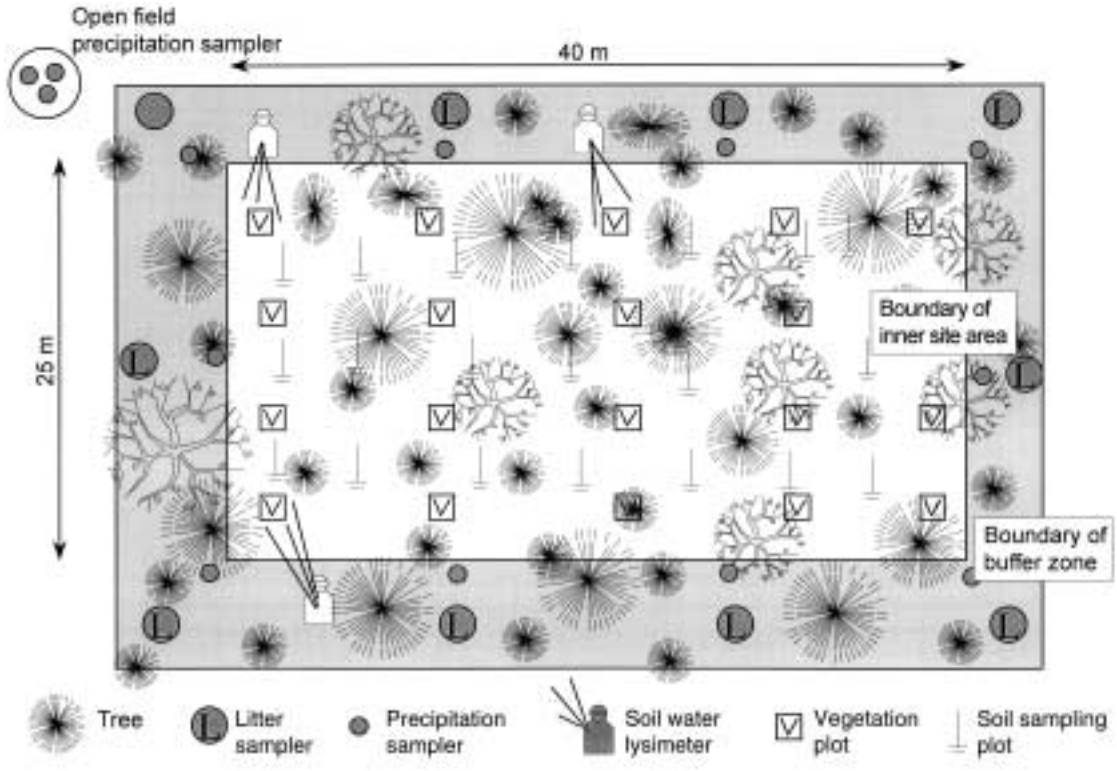

Fig. 2. Site design and equipment placement.

(PA, PB, PC, PD and RUS-1) were located in areas where the critical levels of air pollutants were clearly exceeded, in areas where the critical levels were exceeded occasionally, and outside these areas, giving a gradient from Nikel westwards (Fig. 1). As a guide for location of the sites based on critical levels, the map made by Aamlid *et al*. (1995) was used, as well as modelled levels of SO_2 (Sivertsen *et al*. 1994). An extra site in an unpolluted part of Russia (RUS-0) was selected for some chemical analyses of plant material. All sites were located in boreal Scots pine forests (*Pinus sylvestris*) with dwarf shrubs (*Vaccinium myrtillus, V. vitis-idaea, Empetrum nigrum*) and lichens. Birch trees were present within the PA, PB and RUS-1 and RUS-0 sites. The sites PA, PB and PC were established in 1993, while PD, RUS-1 and RUS-0 were established in 1995.

Each site had an inner area (25×40 m, 0.1 ha) for non-destructive and partly destructive determinations (tree vitality, forest growth, ground vegetation analyses, soil analyses). In addition, each site had a buffer zone outside the inner area where destructive analyses were performed, e.g. branch sampling, and placement of sampling equipment (Fig. 2). Non-destructive analyses of the epiphytic lichen vegetation on tree stems were done on systematically selected trees located in this zone. All corners were permanently marked .

Measurements of SO_2, precipitation, soil water and soil sampling

Sulphur dioxide was sampled using passive SO_2 samplers supplied by the Norwegian Institute for Air Research (NILU). The sampling periods were 14 days. The samplers were analysed by NILU, where the average SO_2 concentration for the specific period was calculated. SO_2 sampling was performed for only one year (1994), and only on Norwegian territory at PA, PB, PC and temporary sites in between. Mathematical modelling was applied to assess the ground air layer pollution over the Russian territory (Gytarsky *et al*. 1997).

We used samples obtained with three precipi-

tation collectors placed in an open area near the site to measure the chemical quality and amount of the open field precipitation (OF) at the sites. To measure the chemical quality and the amount of stand throughfall precipitation (TF) we used precipitation sampled with ten precipitation collectors systematically placed inside the forest stand, i.e. in the buffer zone. Each sampling period was 14 days. The samples were analysed for pH and the main inorganic elements. Precipitation chemistry data were obtained during 1994–1996 for the Norwegian sites only.

Soil water was sampled with lysimeters (PRENART type) placed at a soil depth of approx. 15 cm. The lysimeter cell was attached to a glass bottle by polyethylene tube. By use of an electric (battery) pump, soil water was extracted (–600 millibar) and stored in the bottle. At each site soil water was sampled from three locations, and pooled together for chemical analyses. The sampling period was 14 days and took place at the Norwegian sites only during the growing seasons 1994–1996.

Humus and mineral soils from the layers 0–5 cm, 5–10 cm and 10–20 cm below the humus horizon were sampled from 25 randomly selected locations within the inner site area. The different soil samples from each selected point were pooled together, making four samples of soil to represent the whole site (Aamlid and Venn 1993). The coordinate for the selected locations of soil sampling was stored, making later re-sampling possible.

In order to relate the ground vegetation to soil chemistry, eight soil cores were taken from the upper 5 cm of the humus/soil system adjacent to each vegetation sample plot (*see* below) and pooled together into one soil sample representing every vegetation sample plot. Soil sampling was done once at all sites at site establishment.

Table 1. Scots pine tree characteristics, mean values.

	PA $n = 55$	PB $n = 50$	PC $n = 83$	PD $n = 83$	RUS-1 $n = 48$
Leader length (cm)	11.9	10.0	11.8	13.3	10.8
Tree height (m)	7.9	7.9	9.0	8.2*	6.4
Diameter (cm)	15.6	14.0	14.1	12.6*	10.5

Data from 1995, except * = 1996

Tree measurements

All trees (dbh > 5 cm; dbh = diameter at breast height, 1.3 m above ground) were marked and numbered. Tree height was measured to decimetre accuracy, and the top shoot (leader) length was assessed. The stem circumference was measured 1.3 m above ground to millimetre accuracy. The position at the stem was clearly marked to ensure that future measurements could be made at the same position. Tree measurements were done once at all sites on establishment. Measurements of tree height and diameter and assessment of leader length (Table 1) indicated that there were some differences between the sites. However, these differences are believed to be insignificant when the effects of air pollution on the forest ecosystems are considered.

Crown density was the main variable assessed on the tree crowns. It was estimated in 1% classes on the upper two-thirds of the living tree crown. The crown density of a tree was estimated with reference to a normal dense crown of trees in the region (Aamlid and Horntvedt 1997). Only trained observers using binoculars carried out these assessments. The trees were inspected from all sides and at a distance of about one tree length. Obvious mechanical damage (snow break, wiping), shading or other associated effects were disregarded. Crown colour was estimated using the ICP-Forest classes (ICP Forests 1998); class 0 = normal green, class 1 = slight yellow, class 2 = moderate yellow, class 3 = strong yellow. For the calculations of tree vitality, only non-suppressed trees were included. Damage was recorded for every tree and special attention was paid to symptoms of sulphur dioxide: brown needles (tips) or necrotic parts between the leaf veins (Hartmann *et al*. 1989, Aamlid 1993). Tree crown condition measurement was done annually at all Norwegian sites, while only in 1995 at the Russian sites.

Litterfall was sampled with ten circular collectors (D = 45 cm) systematically placed in the buffer zone. The sampling period was one month, except for the winter periods with snow cover. The amount of litter was dried (105 °C) and weighed, and the percentages of selected components were estimated. Litterfall was sampled during 1994–1995 at the Norwegian sites only.

Plant chemistry

The sampling of plant tissue was done in August. From each of ten identified (numbered) trees in the buffer zone, a branch from the upper part of the tree, facing towards the emission source, was cut down. From Scots pine, the latest three needle age-classes (c, c + 1, c + 2; c = current year) were separately cut off. The needles of these separate needle age-classes from all the ten branches of the ten trees were pooled together to one sample, making three samples of pine needles from each site. From birch there was only one pooled sample based on the leaves from ten trees. Some plant species were sampled outside the inner site area, but never from places that obviously did not represent the site area or from trees where lichen analyses were done. For mosses, the last three annual shoots were cut off as sample material, while the upper half of the living parts from the lichens was analysed. From other plant species, only leaves or needles were analysed. Generally, samples for chemical analysis were handled using disposable gloves made of polyethylene (changed for each sample type), and stored in approved paper bags until further treatment or analysis.

Several plant species were selected: *Pinus sylvestris, Betula pubescens, (Betula nana), Vaccinium myrtillus, V. vitis-idaea, (V. uliginosum, Ledum palustre), Deschampsia flexuosa, Empetrum nigrum, (Juniperus communis), Cladonia stellaris* or *C. rangiferina,* (*Hylocomium splendens), Pleurozium schreberi, (Parmelia olivacea).* If *Salix* was present in the vicinity, a sample of *S. lapponum* was taken. Species given within parentheses were only sampled at the most polluted site (RUS-1) and at the Russian background site (RUS-0).

Ground vegetation and epiphytic lichens

Twenty vegetation sample plots (1 × 1 m, divided into 16 sub-plots, 25 × 25 cm) were randomly placed inside the inner site area. Stems, stumps and large stones had to be avoided, and in those cases, the square was moved to a new location nearby, according to fixed rules. Each sample plot was permanently marked with aluminium sticks pushed into the ground according to the design of an aluminium frame that was used for the analysis of the ground vegetation. In addition, each sample plot was marked with two wooden sticks just outside the square in opposite corners. In each sample plot the %-cover of all species (vascular plants, bryophytes and lichens) was assessed, and their occurrence in each of the 16 equal sub-plots was carefully noted for frequency abundance measurements. The average height of different vegetation layers was measured, and the percentage coverage of each layer, bare soil, stone, litter and dead plants was estimated. Vegetation assessment was done in August at all sites.

The analysis of the epiphytic lichens was carried out on ten Scots pine stems and on ten birch stems, if present (in the buffer zone). On each stem the lichen vegetation was analysed at four levels: 135 cm, 150 cm, 165 cm and 180 cm above ground level, performed separately for the four main aspects: north, west, east and south. The analysis was made by using a simple measuring tape with markers at each centimetre placed around the stem, and the number of markers covering a single species was recorded for each aspect (Aamlid and Venn 1993). Coverage of lichen species was calculated separately for pine and birch trees with regard to height level and aspect, and calculated as percents of stem circumference. Analysis of epiphytic lichens was done at all sites at establishment

Taxonomic nomenclature followed Lid and Lid (1994) for vascular plants, Frisvoll *et al.* (1995) for bryophytes, and Krogh *et al.* (1994) for lichens.

Statistical analysis of ground vegetation

Two different kinds of species abundance values from the vegetation sample plots were used: *percentage cover* and *frequency in subplots*. The percentage cover is the cover of each species projected onto the ground. The subplot frequency value of each species is the number of subplots in one sample plot where the species occurs divided by 16 and multiplied by 100%. The species abundance data, based on frequency in subplots, was

used in ordination and direct gradient analysis.

The following data (I–III), made from the original abundance data, were used to describe the species diversity and floristic composition separately by synusium. A synusium is a group of species, occupying a similar spatial–emporal niche in the plant community. We allocated six synusia within the vegetation sample plots: tree species and shrubs (*Salix* spp.), dwarf shrubs (*Empetrum nigrum*, *Ledum palustre* and *Vaccinium* spp.), herbs and grasses, mosses, liverworts and lichens.

I. *Sample plot frequency per site* for each species: The number of sample plots at the site where the species occurred, divided by 20 and multiplied by 100%.
II. *Characteristic sub-plot frequency per site* for each species: The total number of subplots at the site where the species occurred divided by the number of sample plots where the species occurred and multiplied with 100%. Used in calculating the diversity index for different synusia.
III. *Average values of percentage cover per site* for each species: The sum of the species percentage cover in each of the 20 sample plots divided by 20. Used for calculating the average cover of different synusia at the sites.

Hill's N2 diversity number (Hill 1973a) based on Simpson's (1949) diversity index was calculated on the basis of species abundance separately by synusium under the formula: $D = 1/\sum(p_i)^2$, where p_i is the proportional abundance of the i-th species within the synusium. This diversity number is in units of number of species and reflects mainly the number of very abundant species.

The variation of the species composition in the sample plots were described with indirect gradient analysis (ordination) in terms of correspondence analysis (CA) (Hill 1973b, 1974). This method describes major gradients using species abundance irrespective of any environmental variables. Direct gradient analysis, in terms of canonical correspondence analysis (CCA) (ter Braak 1986, 1987), was used to explain the vegetation gradients by measured environmental variables. Unimodal response models (CA, CCA) was chosen since the length of the vegetation gradient in a detrended correspondence analysis (DCA); (Hill 1979, Hill and Gauch 1980) was more than 2.0 standard deviation units, as recommended by ter Braak and Prentice (1988). The ordinations were performed with the data program CANOCO 3.12 (ter Braak 1988, 1990). Rare species were given less weight by use of the downweighting procedure in the CANOCO program ; otherwise standard options were used. The ordination diagrams were made with the data program CANODRAW 3.0 (Smilauer 1992).

Soil chemical variables (total content of Cu, Ni, N and P; exchangeable H, Ca, Mg and Na; cation exchange capacity (CEC) and base saturation (BS)), percentage cover of tree layer, amount of litter on the ground and a few topographic variables (aspect and slope) were used as the first input data in the direct gradient analysis. A limited number of these environmental variables showed a statistical significant correlation to the vegetation gradients and were further used in the analysis. They represent both natural soil parameters (LOI, pH of a water extract (pH(H_2O)), exchangeable K and Mg, total P and BS) and pollution variables (total content of Ni and Cu in soil).

The variation in the species composition explained by the selected environmental parameters was calculated by dividing the canonical eigenvalue of each parameter in a CCA with the total inertia and multiplying by 100%. The total inertia is the total variation of the species data in a CA. The variation explained by the pollution variables (Ni and Cu in soil), when the variance due to the natural variables was considered, was found by variation partitioning with partial constrained correspondence analysis (Borcard *et al.* 1992, Økland and Eilertsen 1994). The pollution variables were used as the environmental variables and the natural variables as covariables in a CCA. The explained variance is the sum of all the canonical eigenvalues divided by the total inertia and multiplied by 100%.

All statistical tests of environmental variables relations to species composition were made by unrestricted Monte Carlo permutation tests (99 permutations), which are incorporated in the CANOCO program.

Chemical analysis of soil, water and plants

All the chemical analyses of soil, water and plants

were done at NISK, using methods described by Ogner *et al.* (1991). Excess sulphate-sulphur (SO_4-S*) was calculated by using the formula:

$$SO_4\text{-}S^* = SO_4\text{-}S - ([Cl] \times 0.0466)$$

Results

Site characteristics

The main vegetation type at the sites resembles the dryer part of the association Calamagrostio-Pinetum boreale Br.-Bl. et Siss, 39 em. K.-Lund 67 (class Vaccinio-Picetea Br.-Bl. In Br.-Bl., Sissingh et Vlieger 1939, order Cladonio-Vaccinietalia K. -Lund 67, alliance Cladonio-Pinion K. -Lund 86), which is common in the analysed area according to Kielland-Lund (1994). Scots pine was the most abundant tree species at the sites, while *Betula pubescens* was also present. Tree height varied between 6.4 m and 9.0 m (Table 1). The most abundant dwarf shrubs were *Empetrum nigrum, Vaccinium myrtillus, V. vitis-idaea* and *Ledum palustre*. Herbs and grasses had a sparse distribution, except *Linnaea borealis* and *Deschampsia flexuosa*, which were somewhat abundant. The vegetation was generally rich in lichens and oligotrophic mosses. *Cladonia* spp., *Pleurozium schreberi*, *Dicranum fuscescens*, and *D. scoparium* were the most dominant species.

The humus layer at the RUS-1 and PC sites had accumulated large amounts of Ni and Cu compared with the other sites (Table 2) and there was a gradient in the concentration of these two elements from the PA to the RUS-1 site. For other variables given in Table 2 there was no such gradient. The RUS-0 site seemed to be poorer than the others with regard to chemical concentrations in the humus layer (less N and Ca and smaller CEC and BS).

Sulphur dioxide, precipitation and soil water

Analyses using the passive sulphur dioxide samplers showed that there was a measurable gradient in the concentration of sulphur dioxide with highest levels recorded at the PC site (Fig. 3). The mean and maximum recorded levels were comparable to other measurements in the area (Hagen *et al*. 1995). The results also showed that the SO_2 levels could vary considerably across short distances.

Annual mean precipitation and weighted mean concentrations of the most important inorganic compounds of open field precipitation and stand throughfall for the period 1994–1996 are given in Table 3. As expected, pH and the concentration of excess sulphate (SO_4-S*) varied with the distance from the Nikel smelter. The lowest pH was found at the PC site (in open field and stand throughfall precipitation). Among the other elements, there were only minor differences. The nitrogen concentrations were low at all sites.

The soil water at the PC site had a different chemical composition than the soil water from PA, PB and PD (Table 4) with the highest concentrations of several elements, including excess sulphate-sulphur (SO_4-S*). The differences for K and

Table 2. Chemistry of the humus layer (concentrations).

Site	LOI %	pH (water)	Ni µmol kg^{-1}	Cu µmol kg^{-1}	N mmol kg^{-1}	Ca mmol kg^{-1} (E1)	S mmol kg^{-1} (E1)	CEC mmol(+) kg^{-1} (E1)	BS % (E1)
RUS-0	56	3.8	572	340	435	31	2.5	214	43
PA	71	3.8	1243	862	728	52	4.4	280	60
PB	73	3.8	1640	1075	776	60	4.2	297	62
PD	78	3.7	1906	1209	638	47	3.1	272	52
PC	70	3.7	3705	2471	770	59	4.1	282	63
RUS-1	67	4.0	7432	5572	735	55	3.7	269	65

LOI = Loss on ignition, CEC = Cation Exchange Capacity, BS = Base Saturation, E1 = extracted by NH_4NO_3 (according to Ogner *et al.* 1991).

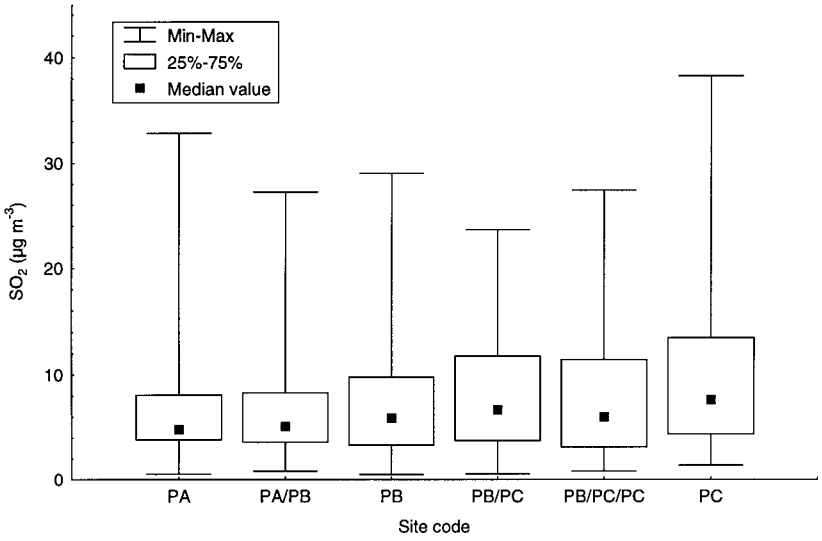

Fig. 3. SO_2 concentrations (µg m^{-3}) at three Norwegian sites (PA, PB and PC) and at three temporary sites in between. *See* Fig. 1 for site codes.

partly for Mg may be an effect of forest operations (thinning) some years previously. The levels of inorganic nitrogen were low at all sites.

Tree crown condition and litter fall

The 1995 data (the only common data year) on

Table 3. Precipitation (mm) and concentrations (weighted mean) for some important components in the precipitation (mean values of 1994. 1995 and 1996) measured as open field precipitation (OF) and stand throughfall (TF).

Site/type	Precipitation mm	LED µS	pH	Cl mg l^{-1}	NO_3-N mg l^{-1}	SO_4-S mg l^{-1}	SO_4-S* mg l^{-1}	Ca mg l^{-1}	K mg l^{-1}	Mg mg l^{-1}	Na mg l^{-1}	NH_4-N mg l^{-1}
PA/OF	434	16.6	4.82	1.33	0.12	0.54	0.52	0.17	0.48	0.07	0.60	0.13
PA/TF	360	23.1	4.66	1.91	0.11	0.78	0.69	0.31	0.46	0.19	1.14	0.08
PB/OF	433	15.8	4.69	1.10	0.11	0.49	0.44	0.15	0.17	0.07	0.64	0.06
PB/TF	427	20.0	4.69	1.60	0.11	0.65	0.58	0.21	0.28	0.14	0.96	0.12
PC/OF	431	20.0	4.62	1.59	0.13	0.67	0.60	0.19	0.21	0.12	0.91	0.08
PC/TF	365	28.7	4.50	2.56	0.14	1.00	0.88	0.32	0.30	0.23	1.52	0.07
PD/OF	445	15.7	4.78	1.32	0.11	0.53	0.47	0.19	0.17	0.09	0.79	0.11
PD/TF	347	24.5	4.61	2.19	0.12	0.85	0.75	0.28	0.31	0.19	1.30	0.11

* = adjusted for sea-salt

Table 4. Soil water chemistry at 15 cm depth below ground level (non-weighted mean).

Site	LED µS	pH	Cl mg l^{-1}	NO_3 -N mg l^{-1}	SO_4-S mg l^{-1}	SO_4-S* mg l^{-1}	Ca mg l^{-1}	Fe mg l^{-1}	K mg l^{-1}	Mg mg l^{-1}	Na mg l^{-1}	NH_4-N mg l^{-1}
PA	31.3	5.85	3.34	0.03	1.86	1.70	1.55	0.11	0.43	0.58	2.53	0.04
PB	18.2	5.54	3.22	0.05	1.60	1.45	0.76	0.12	0.22	0.44	2.72	0.15
PC	51.9	5.15	3.70	0.03	3.56	3.39	3.36	0.47	0.94	1.40	3.58	0.06
PD	37.0	4.84	2.22	0.03	1.61	1.51	1.65	0.42	0.33	0.55	2.61	0.13

* = adjusted for sea-salt

crown condition showed that most of the trees at PA, PB, PC and PD had a crown density score higher than 90%. However, the crown density of the RUS-1 site was lower (Table 5).

The crown colour was normal at all the Norwegian sites (PA, PB, PC and PD), while it was more yellowish on the RUS-1 site. More than 90% of the trees at the PA, PB, PC, and PD sites had crown colour class 1, i.e. normal green. At the RUS-1 site, however, more tree crowns were more or less yellowish in colour (Scots pine 59.3% in class 1 and 24.1% in class 2; birch 45.7% in class 1 and 48.6% in class 2).

The amount of litterfall increased significantly an early autumn due to the annual leaf and needle fall (Fig. 4). Two years of litterfall measurements is too short a time for an evaluation of these data, but they show the expected annual variation in a boreal, pine dominated, forest. The variation between the sites might be due to several factors, such as standing forest volume, tree density and forest management prior to the investigation.

Plant chemistry

Concentrations of Ni and Cu were highest at the RUS-1 site (Table 6) and gradually decreased towards site PA, and even more to site RUS-0, which is located 40 km south of the emission sources (Fig. 1). Lichens and mosses had the highest concentrations of Ni and Cu. The concentrations of Ni and Cu varied among various plant species (Table 7).

Ground vegetation

Cover of synusia, species richness, diversity and floristic composition

The mean percentage cover of tree species and shrubs (*Salix* spp.) within the sample plots was very low on all sites (Fig. 5). The cover of dwarf shrubs was relatively high on all sites, but highest at PC and RUS-1, the two sites nearest to Nikel. The mean percentage cover of herbs and grasses was low at all sites, reflecting the generally low diversity of vascular plants in the oligotrophic plant communities examined. At the Norwegian sites, there was a high mean cover of mosses, especially at sites PA and PC (Fig. 6). As compared with the Norwegian sites, the RUS-1 site had a very low mean cover of both lichens and bryophytes.

The number of species found at the RUS-1 site was lower than the number of species found at the Norwegian sites (Fig. 7) where PC had the lowest species number. All five sites had about the same number of species of trees and shrubs, dwarf shrubs and herbs. The difference in species richness between the sites lies mainly in the occurrence of cryptogams. RUS-1 had relatively few species of lichens, liverworts and mosses, while site PC had a relatively low number of lichens.

Hill's N2 diversity number, where both the number of species and their abundance are taken into consideration, showed that the RUS-1 site had the lowest total diversity (Table 8). This is due to the low diversity in the synusia of lichens, liverworts and mosses.

The dwarf shrubs *Empetrum nigrum* ssp. *hermaphroditum*, *Vaccinium myrtillus*, *V. vitis-idaea*, and *Ledum palustre* occurred on all sites, while *Vaccinium uliginosum* was only found at the RUS-1 site, probably due to a higher soil wetness at this site (Table 9). Several herbs and cryptogams occurred also on all sites. However, the frequency of the bryophytes and the lichens was distinctly lower at the RUS-1 site.

A few bryophytes and some lichens were common at the Norwegian sites, while they were not observed at the RUS-1 site (e.g. *Hylocomium splendens* and several *Cladonia* species.

The indirect gradient analysis (based on the frequency abundance measurements of species within subplots) clearly demonstrated that the species composition at the RUS-1 site was somewhat different from the Norwegian sites, as shown

Table 5. Crown density (%) of Scots pine.

	PA	PB	PC	PD	RUS-1
1993	91.7	96.3	94.6	–	–
1994	92.3	94.1	97.2	–	–
1995	93.1	95.9	96.5	93.4	82.9
1996	90.9	95.5	93.6	93.6	–

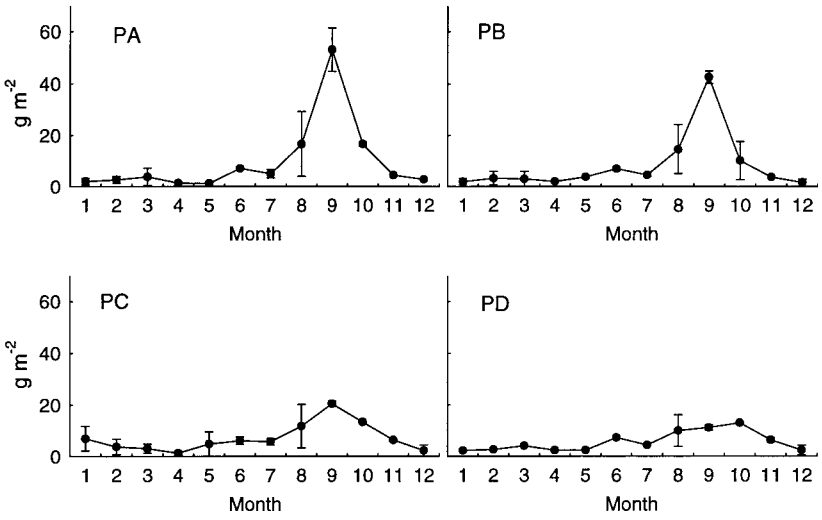

Fig. 4. The variation of monthly litterfall at four monitored sites (Scots pine) (1994–1995). Bars represent 1 standard deviation. *See* Fig. 1 for site codes.

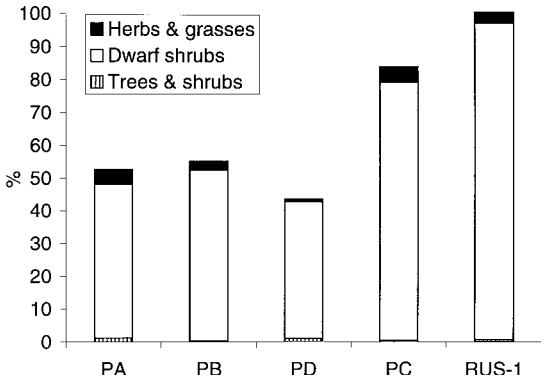

Fig. 5. Mean cover of trees and shrubs, dwarf shrubs and herbs and grasses. *See* Fig. 1 for site codes.

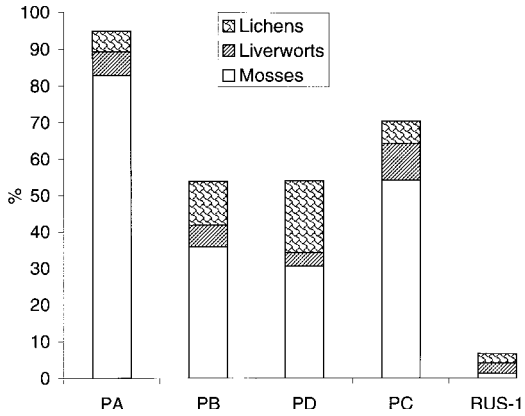

Fig. 6. Mean cover of lichens, liverworts and mosses at the investigated sites. See Fig. 1 for site codes.

by the correspondence analysis (CA) sample plot diagram (Fig. 8) where the sample plots from the RUS-1 site are well separated from the Norwegian sites (PA, PB, PC and PD). The PA and PB sites are most different from the RUS-1 site with respect to species composition, while the PC site, which is geographically located closest to the RUS-1 site, is the most similar.

The species composition of the sample plots can be revealed by comparing the CA sample plot ordination diagram and the CA species ordination diagram (Figs. 8 and 9). Fig. 9 shows that there is a gradient on CA axis 1 from *Vaccinium myrtillus* and *Empetrum* dominated stands with herbs such as *Melampyrum pratense, Trientalis europaea* and *Deschampsia flexuosa* to more lichen rich communities on high CA axis 1 scores. This may reflect an environmental gradient in soil humidity and soil fertility. The sample plots at site PD, and partly at PB, are characterised by a high abundance of lichens, while PA and PC are more dominated by dwarf shrubs and mosses such as *Vaccinium myrtillus, Hylocomium splendens, Pleurozium schreberi* and *Dicranum majus*.

Species characterising the RUS-1 site are shown on low axis 1 scores and high axis 2 scores, such as *Salix phyllicifolia, Salix caprea, Epilobium angustifolium, Ledum palustre* and *Funaria hygrometrica.* Some of these species may indicate a relatively high soil wetness, but the occurrence of *Epilobium angustifolium* and especially the moss *Funaria hygrometrica* may also reflect regeneration stages from earlier forest fires. However, the very low abundance or even the absence

Table 6. Concentrations of mineral elements in some common plant species at different sites.

Species code	Site code	AC	Ca mmol kg^{-1}	Cu µmol kg^{-1}	Fe mmol kg^{-1}	K mmol kg^{-1}	Mg mmol kg^{-1}	Mn mmol kg^{-1}	N mmol kg^{-1}	Ni µmol kg^{-1}	P mmol kg^{-1}	S mmol kg^{-1}	Zn µmol kg^{-1}
Betu pub	PA	*	207	158	1.2	161	136	43.9	1 582	203	73	50	3 542
Betu pub	PB	*	147	168	1.5	139	125	22.0	1 434	243	61	44	2 077
Betu pub	PC	*	115	202	1.6	151	109	15.5	1 429	396	70	44	2 505
Betu pub	PD	*	170	201	1.9	141	139	23.7	1 528	261	80	50	1 967
Betu pub	RUS-1	*	135	175	2.1	176	120	22.0	1 345	641	91	45	1 559
Betu pub	RUS-0	*	122	90	1.3	173	94	15.2	1 313	105	83	38	2 135
Cla ste	PA	*	17	485	7.7	44	14	2.9	315	683	23	18	300
Cla ste	PB	*	16	532	8.6	45	15	2.2	338	814	22	18	296
Cla ste	PD	*	6	695	11.5	31	11	0.5	260	904	12	15	193
Cla ste	RUS-1	*	6	1945	25.4	45	17	0.7	338	2 567	21	26	343
Cla ste	RUS-0	*	9	170	2.9	34	9	1.4	237	241	19	13	207
Desc fle	PA	*	33	76	0.8	467	34	11.7	930	119	78	30	587
Desc fle	PB	*	29	143	1.2	328	32	9.3	946	159	30	30	363
Desc fle	PC	*	36	164	1.4	393	33	10.6	844	298	46	31	391
Desc fle	PD	*	34	106	1.4	334	38	8.2	1 108	107	30	34	298
Desc fle	RUS-1	*	38	100	1.2	409	41	10.5	883	346	59	35	335
Desc fle	RUS-0	*	30	60	1.0	462	39	5.8	1 017	113	59	37	236
Empe nig	PA	*	139	181	1.7	118	53	12.2	695	325	38	37	162
Empe nig	PB	*	121	303	3.0	103	72	7.4	689	532	37	39	218
Empe nig	PC	*	105	433	4.2	142	64	5.4	650	752	37	39	179
Empe nig	PD	*	149	249	3.6	108	88	6.6	773	503	41	42	171
Empe nig	RUS-1	*	112	423	5.6	160	67	4.3	659	935	38	41	140
Empe nig	RUS-0	*	132	130	1.0	144	65	10.1	833	224	45	48	236
Pinu syl	PA	c0	50	129	0.6	234	59	10.7	1 134	152	87	41	717
Pinu syl	PA	c1	54	107	1.0	84	38	11.3	626	120	32	22	500
Pinu syl	PA	c2	75	126	1.5	79	33	14.6	663	146	31	23	549
Pinu syl	PB	c0	45	123	0.6	166	50	8.1	1 295	137	92	44	598
Pinu syl	PB	c1	99	96	1.2	78	55	14.7	866	163	43	36	658
Pinu syl	PB	c2	106	179	1.9	71	42	13.9	790	185	33	30	582
Pinu syl	PC	c0	47	205	0.9	269	50	6.6	1 299	311	97	53	766
Pinu syl	PC	c1	76	238	2.6	114	48	10.0	831	456	43	38	677
Pinu syl	PC	c2	92	266	3.2	105	40	11.9	828	475	42	35	724
Pinu syl	PD	c0	39	173	0.8	219	49	6.0	1203	259	97	44	736
Pinu syl	PD	c1	59	183	2.2	87	48	9.0	747	296	40	30	585
Pinu syl	PD	c2	80	193	2.7	83	40	11.1	754	283	39	28	606
Pinu syl	RUS-1	c0	58	154	1.5	192	42	7.5	1 009	327	73	39	439
Pinu syl	RUS-1	c1	107	318	5.5	114	44	14.0	803	576	43	37	393
Pinu syl	RUS-1	c2	117	394	6.9	102	41	12.7	781	671	38	36	353
Pinu syl	RUS-0	c0	47	61	0.6	155	49	8.6	1 023	123	68	36	539
Pinu syl	RUS-0	c1	74	73	1.1	86	44	11.8	763	104	39	28	511
Pinu syl	RUS-0	c2	105	80	1.4	80	40	13.5	728	129	37	28	566
Pleu sch	PB	*	106	1 584	25.7	107	55	12.7	906	2 461	52	50	1 015
Pleu sch	PC	*	73	2 594	27.0	173	51	8.7	503	3 756	46	42	607
Pleu sch	PD	*	69	1 083	15.6	170	56	8.9	464	1 570	46	35	476
Pleu sch	RUS-1	*	80	2 226	25.9	265	85	11.7	660	3 591	84	49	578
Pleu sch	RUS-0	*	45	258	3.0	151	44	8.2	410	433	47	30	384
Vacc myr	PA	*	211	149	1.1	276	90	55.8	1 143	125	67	77	259
Vacc myr	PB	*	201	181	0.9	131	129	27.2	1 041	118	43	57	148
Vacc myr	PC	*	170	171	1.2	211	76	40.6	1 061	217	46	67	158
Vacc myr	PD	*	289	192	0.9	138	151	61.4	1 042	117	50	67	176
Vacc myr	RUS-1	*	186	160	1.5	215	86	33.9	1 082	298	55	82	173
Vacc myr	RUS-0	*	194	99	0.8	146	92	40.2	1 024	43	58	53	163
Vacc vit	PA	*	159	51	0.6	79	39	46.5	649	26	28	59	349
Vacc vit	PB	*	180	143	0.8	85	60	24.5	616	108	30	74	353
Vacc vit	PC	*	115	135	0.9	106	46	32.5	492	141	19	66	432
Vacc vit	PD	*	123	130	1.1	96	49	26.5	473	147	19	68	200
Vacc vit	RUS-1	*	152	140	1.8	115	44	24.6	545	318	25	84	224
Vacc vit	RUS-0	*	169	58	0.5	101	57	28.2	648	39	37	73	320

Species codes: Betu pub = *Betula pubescens*, Clad ste = *Cladina stellaris*, Desc fle = *Deschampsia flexuosa*, Empe nig = *Empetrum nigrum*, Pinu syl = *Pinus sylvestris*, Pleu sch = *Pleurozium schreberi*, Vacc myr = *Vaccinium myrtillus*, Vacc vit= *Vaccinium vitis-idaea*.
AC: age class, c0 = current year, c1 = last year, c2= second last year, * = not relevant

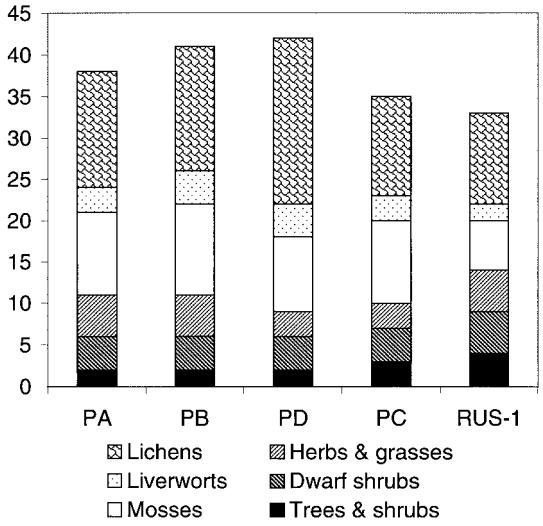

Fig. 7. Number of plant species, grouped by synusium. *See* Fig. 1 for site codes.

of at the RUS-1 site of mosses which are normally found in boreal pine forests, such as *Dicranum* species, *Hylocomium splendens* and *Pleurozium schreberi,* was most remarkable.

Table 7. The relative accumulation of Cu. Fe. Ni and S in plant tissue given as the ratio between RUS-1 (polluted) and RUS-0 (non-polluted).

Plant species	Cu	Ni	Fe	S
Trees				
Betula pubescens	1.9	6.1	1.7	1.2
Pinus sylvestris				
needles 1993 +1994	4.7	9.8	5.0	1.0
needles 1995 (= c0)	2.5	2.7	2.4	1.1
Juniperus communis	4.0	3.5	3.3	1.2
Salix lapponica	1.4	3.9	1.7	2.2
Shrubs				
Betula nana	2.4	3.9	3.2	1.2
Vaccinium vitis-idaea	2.4	8.1	3.4	1.2
Vaccinium myrtillus	1.6	7.0	1.9	1.5
Empetrum nigrum	3.2	4.2	5.8	0.9
Ledum palustre	3.8	4.5	6.9	1.1
Vaccinium uliginosum	1.2	2.2	1.2	1.5
Grasses				
Deschampsia flexuosa	1.6	3.1	1.1	0.9
Mosses and lichens				
Cladonia stellaris	11.4	10.7	8.9	2.0
Cladonia rangiferina	10.2	9.1	8.2	1.7
Parmelia olivacea	7.7	7.4	7.7	1.8
Pleurozium schreberi	8.6	2.7	2.4	1.6

Vegetation–environment relationships

Direct gradient analysis, performed by canonical correspondence analysis (CCA), was used to detect patterns of variation in the species data that could be explained by the observed environmental variables. The CCA analysis showed that the variation in species composition is well correlated to some of the measured environmental variables (Tables 10 and 11, and Fig. 10). The explained percentage variance of the species on CCA axis 1 was 13.6% and of the first four CCA axes 25%, and the explained relation between the species and the environmental variables was rather high, 50% on axis 1 and 90% on the first four axes.

Base saturation (BS) in the upper soil was the most important variable, explaining 11.7% of the species variation (Table 11). Loss on ignition (LOI) and pH(H_2O) explained least of the species variation, 4.4% and 4.1% respectively. All variables were significantly correlated to the species variation at $p = 0.01$.

The first ordination axis is probably a soil fertility axis and the second axis may reflect the pollution gradient from site RUS-1 to site PA with decreasing values of Ni and Cu in the soil. The CCA diagram shows that the species composition at RUS-1 and partly at PC, which are the sites closest to Nikel, are correlated with high values of Cu and Ni and with high base saturation in the soil. The natural environmental variables explained 19.6% of the species variation after the variation due to the pollution variables had been considered, and the pollution variables explained 2.8% of the species variation when the variation due to natural environmental variables had been considered. Both sets of variables were found to

Table 8. Hill's N2 diversity number calculated on a basis of characteristic weighted sum of subplots.

Synusium	PA	PB	PD	PC	RUS-1
Trees	2.0	1.7	1.9	2.8	3.3
Dwarf shrubs	3.5	3.6	3.4	3.6	4.2
Herbs	4.3	4.1	2.9	2.4	2.9
Mosses	7.6	6.8	6.5	5.1	4.3
Liverworts	1.7	2.4	2.8	1.9	1.4
Lichens	9.1	9.7	14.0	10.1	8.1
All species	25.5	26.0	28.6	20.1	14.0

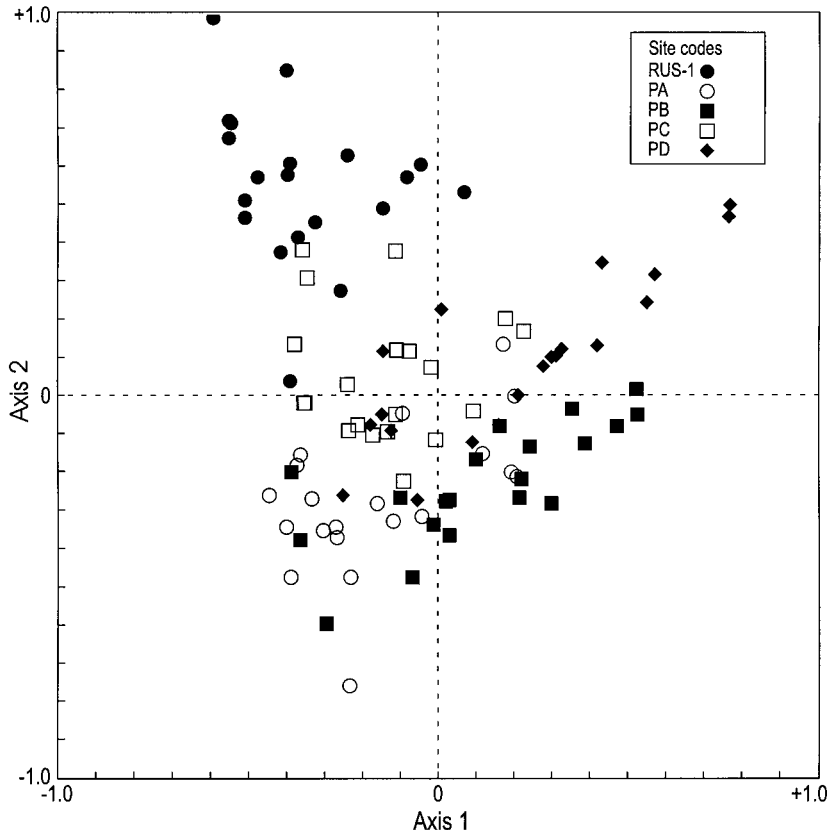

Fig. 8. Correspondence analysis (CA) diagram axes I and II. of the vegetation sample plots with their site membership shown. The sample plots that are close together correspond to plots that are similar in species composition. *See* Fig. 1 for site codes.

be statistically significantly correlated to the species variation (the natural variables at $p < 0.01$, and the pollution variables at $p < 0.03$). However, the explained variation (2.8%) is low, and it may not necessarily be adequate in the discussion of air pollution impacts.

Epiphytic lichens

Epiphytic lichens were more frequent on the birch stems than on the pine stems at sites where both tree species occurred, though epiphytic lichens were found on more than 50% of the pine trees studied. The most common lichens on birch stems were: *Hypogymnia physodes, Parmelia olivacea, Parmeliopsis ambigua* and *Bryoria sp*. *Parmelia. olivacea* was most frequently observed at the Norwegian sites; while *Parmeliopsis ambigua* was most frequent at the RUS-1 site. The largest mean lichen cover on birch stems was observed at the PA site and the coverage became gradually reduced with decreasing distance from the pollution source (PA: 12%, PB: 3%, RUS-1: 1,9%). On pine there was an opposite trend in the lichen cover compared to the pollution gradient (PA: 0.08%, PB: 0,11%, PC: 0.0%, PD: 0.0% and RUS-1: 0.32%). However, the lichen cover was very low and several trees had no lichens at all.

The lichen cover at the Norwegian sites decreased with increasing height on the stem when comparing all the epiphytic lichen species observed. Such a tendency was not observed at the RUS-1 site. Most lichen cover was observed on the northern and western aspects distal to the emission sources (Fig. 11). This tendency seemed to be more evident at the most polluted site (RUS-1) where only *Parmeliopsis* sp. was found on the south and east facing aspects.

Discussion

The sites were all selected in an air pollution gradient verified by passive SO_2 sampling and intensive air monitoring by the Norwegian Institute for

Table 9. Sample plot frequency per site.

Synusium	Species	PA	PB	PD	PC	RUS-1
Trees & shrubs						
	Betula pubescens		10	25		20
	Pinus sylvestris		15	25	20	
	Sorbus aucuparia	5			5	25
	Populus tremula				5	
	Salix caprea					10
	Salix myrsinifolia ssp. *myrsinifolia*	5				
	Salix phylicifolia					5
Dwarf shrubs						
	Empetrum nigrum ssp. *hermaphroditum*	95	100	90	100	100
	Ledum palustre	10	10	45	40	90
	Vaccinium myrtillus	95	100	70	95	100
	Vaccinium vitis-idaea	90	100	100	100	100
	Vaccinium uliginosum					30
Herbs and grasses						
	Linnaea borealis	55	20	10	85	75
	Deschampsia flexuosa	100	90	65	95	95
	Diphasiastrum complanatum ssp. *montellii*		5	5		
	Lycopodium annotinum				5	10
	Trientalis europaea	15	20			
	Cornus suecica		30			
	Epilobium angustifolium					10
	Listera cordata					5
	Lycopodium clavatum	10				
	Melampyrum pratense	5				
Mosses						
	Pleurozium schreberi	100	100	85	95	20
	Pohlia nutans	20	50	90	80	35
	Polytrichum juniperinum	25	25	35	10	5
	Dicranum fuscescens	75	95	30	85	
	Dicranum scoparium	45	40	95	90	
	Hylocomium splendens	85	35	30	55	
	Polytrichum commune	50	90	40		30
	Dicranum polysetum	20		60	10	
	Plagiothecium laetum		15	5	15	
	Dicranum bergeri	15	5			
	Dicranum majus	20			10	
	Barbula sp.		5			
	Brachythecium rutabulum				5	
	Bryum sp.		10			
	Funaria hygrometrica					25
	Tetraplodon mnioides					5
Liverworts						
	Barbilophozia sp.	100	100	85	100	60
	Lophozia ventricosa coll.	25	75	30	55	5
	Ptilidium ciliare	20	20	25	5	
	Cephalozia sp.			5		
	Cephaloziella spinigera		5			
Lichens						
	Cladonia deformis/sulphurina	25	55	65	40	45
	Cladonia arbuscula coll.	60	80	75	45	15
	Cladonia chlorophaea coll.	45	70	70	55	5
	Cladonia crispata	40	85	70	40	15

Continued

Table 9. Continued.

Synusium	Species	PA	PB	PD	PC	RUS-1
	Cladonia furcata	5	50	50	15	5
	Cladonia gracilis/cornuta	80	90	95	80	60
	Cladonia rangiferina	75	90	95	65	40
	Cladonia carneola	5	55	45	10	
	Cladonia coccifera/pleurota	20	45	35	25	
	Cladonia squamosa	10	15	15	5	
	Cladonia stellaris	20	60	55		
	Cladonia uncialis	10	40	60		
	Cladonia bellidiflora	5	5		5	
	Cladonia botrytes		5			20
	Cladonia cenotea			25		5
	Cetraria ericetorum			5		
	Cetraria islandica			5		
	Cetraria nivalis			5		
	Cladonia cervicornis ssp. verticillata			5		
	Cladonia coniocraea					5
	Cladonia digitata			5		
	Cladonia macrophylla			10		
	Cladonia sp.					10
	Cladonia subulata				5	
	Nephroma arcticum		5			
	Peltigera aphthosa			30		
	Peltigera scabrosa	5				

Number of sample plots with the species present divided by 20 then multiplied by 100.

Air Research (Sivertsen *et al*. 1994). Chemical analyses of humus showed that the forest floor was influenced by air pollutants, i.e. elevated concentrations of Ni and Cu were found. The other chemical properties (including pH) of the humus layer did not show such a pattern. This agrees with results reported by Derome *et al*. (1998). However, in other studies pH and concentrations of other elements are also reported as varying with distance from the pollution source (Lukina and Nikonov 1995, Øvrevoll *et al*. 1995, Lindroos *et al*. 1998, Derome and Lindroos 1998). Helmisaari *et al* (1999) found root damage at 0.5 km distance to a smelter in south-western Finland, but not at 4

Table 10. Ordination results of the axes in correspondence analysis (CA) and canonical correspondence analysis (CCA).

		1	2	3	4	Ti	*S*
CA						1.09	
	λ	0.267	0.138	0.095	0.065		
	V_s	24.4	37.0	45.7	51.6		
CCA							0.298
	λ	0.149	0.073	0.037	0.014		
	r	0.773	0.743	0.641	0.575		
	V_s	13.6	20.3	23.7	25.0		
	V_{s-e}	50.0	74.4	86.9	91.6		

λ = Eigenvalue. *r* = species–environment correlation. V_s = explained cumulative percentage variance of the species data. V_{s-e} = cumulative percentage variance of the species–environment relation (variation explained by the canonical axes). Ti = total inertia (sum of all unconstrained eigenvalues). *S* = sum of all canonical eigenvalues.

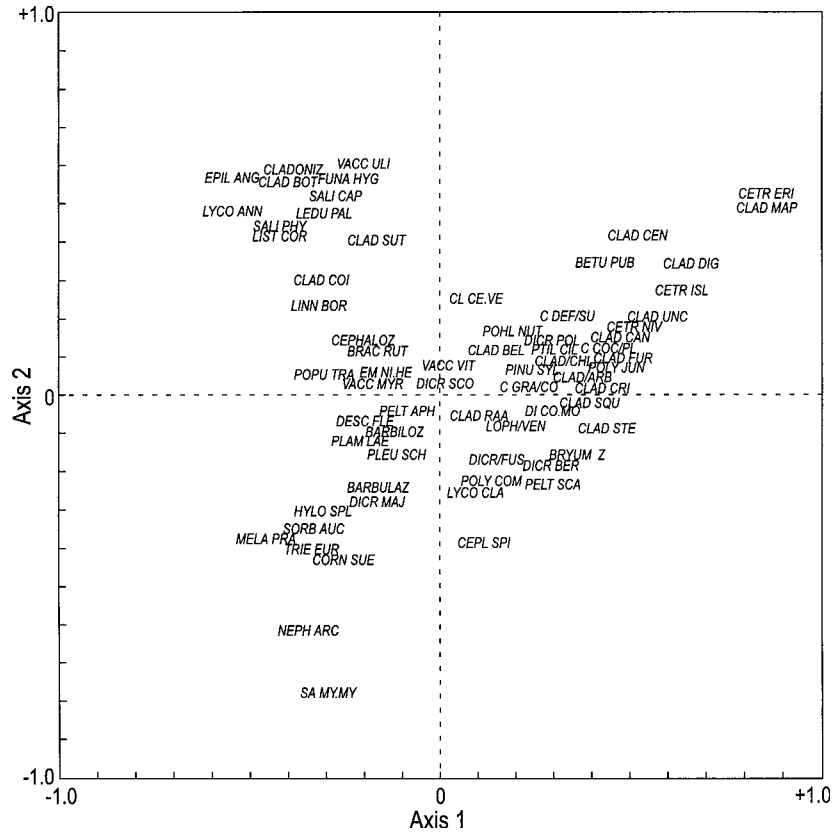

Fig. 9. Correspondence analysis (CA) diagram axes I and II. of species. The species are located in the ordination space according to their optimum abundance values in the vegetation samples.

and 8 km distance. It is therefore not likely that the level of air pollution at the plots in the current study is high enough to cause root damage.

It is too early to evaluate the increment data for stand structure, such as tree height, stem circumference and leader length. However, reduced growth may be expected (Nöjd and Reams 1996, Nöjd *et al*. 1996). Except for these basic facts, general data on forest properties and vegetation type showed that the sites were relatively similar to each other and therefore seemed to be suitable for long-term ecosystem monitoring of these north boreal pine forest ecosystems.

The chemical analysis of precipitation and soil water clearly demonstrated that the sites were situated in an air pollution gradient. However, rainfall pH was higher than the acid rain affected stands in southern Norway, although lower than measurements from pristine areas (SFT 1999). The concentration of sulphur in OF precipitation was

Table 11. The environmental variables explanation of the variation in the species data and their significance level.

	BS	K	Cu	Ni	Mg	P	LOI	pH
λ	0.128	0.085	0.072	0.070	0.070	0.070	0.049	0.045
V	11.7***	7.8**	6.6**	6.4**	6.4**	6.4**	4.4**	4.1**

λ = Eigenvalue of the first axis in a CCA of the one environmental variable. V = [λ/sum of all unconstrained eigenvalues in a CA] $\times$ 100 = percentage variation in the species data explained by the environmental variable
** = Significant ($p \leq 0.01$) in unrestricted Monte Carlo permutation tests (99 permutations)
BS = Base Saturation, LOI = Loss on ignition

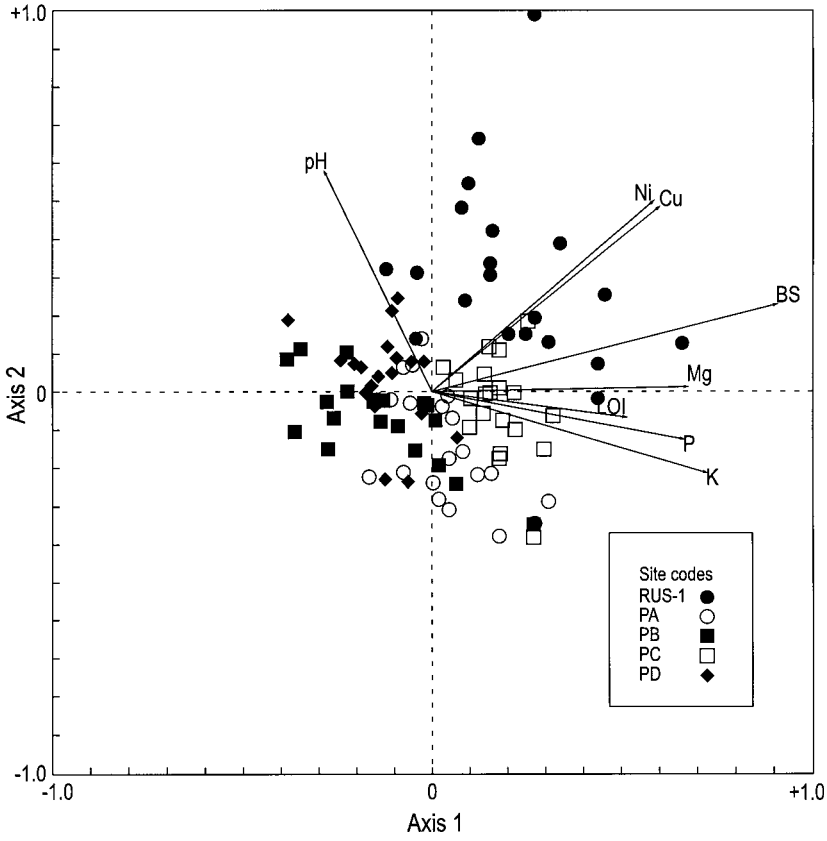

Fig. 10. Canonical correspondence analysis (CCA) bi-plot diagram. axes 1 and 2. of the sample plots and the environmental variables. Environmental variables are visualised as arrows. The arrows point in the direction where the environmental variable has its highest values in the sample plots. The lengths of the arrows are proportional to their importance in explaining the variation in the species composition. *See* Fig. 1 for site codes.

at a similar level as in acid rain in southern Norway (SFT 1999). However, the concentration of SO_4-S in TF precipitation decreased with increasing distance to the emission source, as also reported by Karaban and Gytarsky (1995). The concentration levels were comparable with results from East Germany (Bruggemann and Spindler 1999). The concentrations of NO_3-N, NH_4-N, Mg and Ca did not show any dependence on distance to the smelter, in agreement with the findings of Karaban and Gytarsky (1995).

The crown condition at the RUS-1 site has been negatively influenced by air pollution. However, in general it is difficult to identify effects of air pollution on forest ecosystems based on the crown density parameter only. A forest ecosystem is complex, and several simultaneous influences of biotic and abiotic factors are acting (Innes 1993, Landmann and Bonneau 1995). Fungal attacks may cause considerable crown thinning on Scots pine in boreal forests (Kaitera *et al*. 1995).

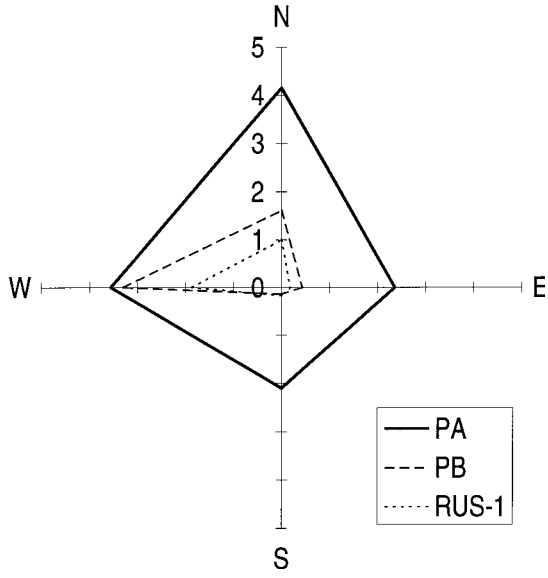

Fig. 11. Lichen cover on birch stems for different aspects (Percent stem circumference). *See* Fig. 1 for site codes.

Forest ecosystems respond in a similar and non-specific manner to the influence of several different environmental factors. It should also be taken into consideration that the crown density parameter is a subjective one that depends on the individual observer's experience. However, the research area was described by a number of researchers as an area where severe damage to forests is frequently observed (Gytarsky *et al* 1995, Regina and Kozlov 2000, Vassilieva *et al*. 2000). Increased litterfall may appear after air pollution episodes (high SO_2-levels) that lead to dead needles and leaves. The litterfall data show that the pine trees had enough needles to drop older needles at autumn as is usual for Scots pine.

Elevated concentrations of some chemical elements in plant tissue, as well as ratios between elements, might be a consequence of industrial emissions (Kozlov *et al*. 2000). Sulphur dioxide and aerosols of nickel, copper, and iron are the main components of the industrial emissions in the study area. Concentrations of sulphur were higher in samples of lichens, mosses, and some species of shrubs compared with samples from the remote background site (RUS-0). Considering groups of plant species, the following order according to the accumulation ratio of the main contaminants could be set up: mosses and lichens > shrubs > trees > herbs. More pollutants were accumulated by the coniferous than by the deciduous species. High concentrations of nickel, copper and iron were observed in the samples of *Vaccinium vitis-idaea* and *V. myrtillus*. Lower concentrations were found in *Empetrum nigrum* and *Vaccinium uliginosum.* These four species may be tolerant of air pollution (Alexeyev 1995). This variation in concentrations among different plant species may be due to several causes, e.g. soil properties, root distribution, leaf surface and plant physiology (Kozlov *et al*. 2000, Steinnes *et al*. 2000). The concentrations of toxic elements were not sufficient to cause visible damage during the observation period. However, visible symptoms of SO_2 damage are reported from the area (Aamlid 1992, Alexeyev 1995). A large variation in levels of metal concentrations in different plant species from the Kola Peninsula are published (Gytarsky *et al*. 1995, Kozlov *et al* 1995, Derome and Nieminen 1998, Chernenkova and Kuperman 1999)

In the pollution gradient from site PA to RUS-1 the most important differences in the species composition were related to the loss of the species richness and the lower abundance of bryophytes and lichens at the Russian site. The soil fertility explained most of this variation in the plant communities. However, the pollution impact, given as the amount of Ni and Cu in soil, was significantly correlated with the differences in the species composition. This correlation is a strong indication that the air pollution load had an impact on the species composition of the ground vegetation. Elevated levels of SO_2 are toxic to lichens, which may partly contribute to their lower coverage and diversity. The same reduction in ground lichens has also been reported by Tømmervik *et al*. (1995), Chernenkova and Kuperman (1999) and Aarrestad and Aamlid (1999) as an effect of emissions from nickel-copper smelters in Nikel and Zapolyarnyy.

Mosses are in general considered to be less sensitive to heavy metals than lichens. However, elevated bioavailable copper is toxic to most bryophytes (e.g. Shaw 1990), and the variation in growth form among mosses has been suggested as a possible explanation of different sensitivity to heavy metals (Lepp and Salmon 1999). The latter authors showed that pleurocarpous mosses are more sensitive to soil copper content than acrocarpous mosses, due to different ways of taking up water. In our study, five out of six mosses recorded on the Russian plot were acrocarpous, which may support this hypothesis. However, several acrocarpous mosses, such as all the *Dicranum* species which are common on the Norwegian side, disappear on the more polluted Russian plot (RUS-1).

Even though some of the variation in species composition can be explained by soil fertility and to some extent the pollution impact, the partial constrained analysis showed a high degree of unexplained variation. This indicates that important environmental variables which may affect the vegetation have not been measured, e.g. soil humidity, microclimate and micro-topography. In addition, the human influence on the sites should also be taken into consideration, e.g. forest management, forest fire, erosion and trampling. The high unexplained variation might also be a result of methodological problems in partitioning the

total variation in the data set, cf. Økland (1999).

There was generally a larger lichen cover on birch than on pine stems. However, the decrease in lichen cover with distance to the pollution source on pine was opposite to that on birch. This was the case for the species *Hypogymnia physodes*, *Parmeliopsis ambigua* and *Bryoria* sp., all of which are common on pine stems in the area. Otherwise, the coverage of *Parmeliopsis ambigua* was higher at the RUS-1 site than at the Norwegian sites. This might be due to natural conditions, although *Parmeliopsis* sp. is reported to be tolerant to air pollution (Kauppi and Halonen 1992) or it may be favoured due to lack of concurrent species. Tree diameter might also be of importance here, but the number of assessed trees was too low for evaluation. For birch trees, there was an increased coverage and number of species with increasing distance to the pollution source. This was mostly due to *Parmelia olivacea*. The data revealed also that lichens were more common on the northern and western aspects of the stems than on southern and eastern aspects. This too, seemed to be more pronounced at the RUS-1 site, but once again there were too few observations for a full evaluation. The level above ground where lichens are found might also be a consequence of air pollution, but also here the data set was not large enough to have it statistically evaluated. Such data should be included in future investigations on the sites.

The aim of the current project was to draw conclusions on the ecological condition of the forest ecosystem in the border areas between Norway and Russia. Such a project is integrated in its nature, and huge amounts of data are included in the its database. The data, which consists of several data types (e.g. data for trees, precipitation, soil and soil water and leaf/needle chemistry) are all collected within small site areas. This is an important advantage of integrated data sampling. These data may therefore be of high value for research on specific topics related to air pollution impact on boreal ecosystems.

Conclusions

The air pollution in the border areas between Norway and Russia is well documented. We believe that the observed differences in the ecological state and diversity among the research sites are due to the air pollution load in the area. The elevated concentrations of Ni and Cu in plant tissue, the reduced lichen vegetation on stems and on the forest floor, and the reduced or absent moss vegetation are the most obvious impacts in the investigated area.

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Appendix. Abbreviations, codenames of species .

Trees, shrubs and dwarf shrubs	
BETU PUB	*Betula pubescens*
EM NI.HE	*Empetrum nigrum* ssp. *hermaphroditum*
LEDU PAL	Ledum palustre
PINU SYL	*Pinus sylvestris*
POPU TRA	*Populus tremula*
SA MY.MY	*Salix myrsinifolia* ssp. *myrsinifolia*
SALI CAP	*Salix caprea*
SALI PHY	*Salix phylicifolia*
SORB AUC	*Sorbus aucuparia*
VACC MYR	*Vaccinium myrtillus*
VACC ULI	*Vaccinium uliginosum*
VACC VIT	*Vaccinium vitis-idaea*
Herbs	
CORN SUE	*Cornus suecica*
DI CO.MO	*Diphasiastrum complanatum* ssp. *montellii*
EPIL ANG	*Epilobium angustifolium*
LINN BOR	*Linnaea borealis*
LIST COR	*Listera cordata*
LYCO ANN	*Lycopodium annotinum*
LYCO CLA	*Lycopodium clavatum*
MELA PRA	*Melampyrum pratense*
TRIE EUR	*Trientalis europaea*
Grasses	
DESC FLE	*Deschampsia flexuosa*
Mosses	
BARBULAZ	*Barbula* sp.
BRAC RUT	*Brachythecium rutabulum*
BRYUM Z	*Bryum* sp.
DICR BER	*Dicranum bergeri*
DICR MAJ	*Dicranum majus*
DICR POL	*Dicranum polysetum*
DICR SCO	*Dicranum scoparium*
DICR/FUS	*Dicranum fuscescens*/*flexicaule*
FUNA HYG	*Funaria hygrometrica*
HYLO SPL	*Hylocomium splendens*
PLAM LAE	*Plagiothecium laetum*
PLEU SCH	*Pleurozium schreberi*
POHL NUT	*Pohlia nutans*
POLY COM	*Polytrichum commune*
POLY JUN	*Polytrichum juniperinum*
Liverworts	
BARBILOZ	*Barbilophozia* spp.
CEPHALOZ	*Cephalozia* spp.
CEPL SPI	*Cephaloziella spinigera*
LOPH/VEN	*Lophozia ventricosa*
PTIL CIL	*Ptilidium ciliare*
Lichens	
C COC/PL	*Cladonia deformis*/*sulphurina*
C DEF/SU	*Cladonia coccifera*/*pleurota*
C GRA/CO	*Cladonia gracilis*/*cornuta*
CETR ERI	*Cetraria ericetorum*
CETR ISL	*Cetraria islandica*
CETR NIV	*Cetraria nivalis*
CL CE.VE	*Cladonia cervicornis* ssp. *verticillata*
CLAD BEL	*Cladonia bellidiflora*
CLAD BOT	*Cladonia botrytes*
CLAD CAN	*Cladonia carneola*
CLAD CEN	*Cladonia cenotea*
CLAD COI	*Cladonia coniocraea*
CLAD CRI	*Cladonia crispata*
CLAD DIG	*Cladonia digitata*
CLAD FUR	*Cladonia furcata*
CLAD MAP	*Cladonia macrophylla*
CLAD RAA	*Cladonia rangiferina*
CLAD SQU	*Cladonia squamosa*
CLAD STE	*Cladonia stellaris*
CLAD SUT	*Cladonia subulata*
CLAD UNC	*Cladonia uncialis*
CLAD/ARB	*Cladonia arbuscula* coll.
CLAD/CHL	*Cladonia chlorophaea* coll.
CLADONIZ	*Cladonia* sp.
NEPH ARC	*Nephroma arcticum*
PELT APH	*Peltigera aphthosa*
PELT SCA	*Peltigera scabrosa*