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Effects of air pollution from a nickel–copper industrial complex on boreal forest vegetation in the joint Russian–Norwegian–Finnish border area

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The effect of air pollution from the Petchenganickel industrial complex, northwestern part of the Kola Peninsula, on forest vegetation was studied by combining three dormant monitoring networks in Finland, Russia and Norway, comprising a total of 21 plots that were revisited in 2004. Chemical composition of precipitation was monitored during 2004–2005, and indicated continuing high deposition of heavy metals and SO_2 in the border area. The cover of epiphytic lichens on the trunks of downy birch (*Betula pubescens*) and Scots pine (*Pinus sylvestris*) was severely affected by pollution, and there was also a consistent negative effect on the abundance and richness of lichens and bryophytes on the forest floor in a more limited area. The effects of pollution on crown condition and stand growth were weak or absent. This study is an important reference for evaluating the effects of the planned renovation of the smelter in Nikel.

Introduction

The border area between Russia, Norway and Finland belongs to the north boreal and low-alpine vegetation regions and is covered by forest, alpine heathland, bogs and fens (Moen 1999). The area has been severely affected by sulphur dioxide (SO_2) and heavy metal emissions since nickel and copper processing started in Kolosjoki (later called Nikel) in 1942 (Jacobsen 2007). Emissions from the smelter in Nikel and roasting factory in Zapolyarnyy, which since 1946 has constituted the Petchenganickel Mining & Metallurgical Combine (Jacobsen 2007), peaked at approximately 380 000 t SO_2 in 1979 (Henriksen *et al*. 1997), but have now been reduced to about 120 000 t year^{-1} (Milyaev and Yasenskij 2004, cited after Kozlov and Zvereva 2007a). However, the SO_2 emissions from the Nikel smelter alone are still 5–6 times higher than the total Norwegian SO_2 emissions (Hagen *et al*. 2006). The annual emissions of copper and nickel during the period with the highest SO_2 emissions were about 500 and 300 t, respectively (Aamlid 2002).

Air pollution has caused major environmental problems in the northwestern part of the Kola Peninsula, and the vegetation has been changed or destroyed. The cover of epiphytic lichens around the smelters has been drastically reduced (Aamlid *et al*. 2000, Aamlid and Skogheim 2001, Bjerke *et al*. 2006), and the composition of the ground vegetation has been severely affected. In particular, the abundance of epigeic mosses and lichens has been reduced (Tømmervik *et al*. 1998, 2003). In the years with extremely high industrial emissions, visible injuries caused by SO_2 were observed on many species including Scots pine (*Pinus sylvestris*), downy birch (*Betula pubescens*), dwarf birch (*B. nana*) and bilberry (*Vaccinium myrtillus*) (Aamlid 1992). Heavy metals have accumulated in the plant tissues and soil, and there are clear signs of decreased soil fertility and increased soil acidity (Lukina and Nikonov 1997, Derome *et al*. 1998, Aamlid *et al*. 2000, Steinnes *et al*. 2000). Thus, the condition of the terrestrial biota, as well as of lakes and rivers (Traaen *et al*. 1991), has been drastically affected. 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 about 90%, thereby substantially decreasing the pollution impact in the region by 2009 (Stebel *et al*. 2007).

Over the years several projects have been implemented for monitoring the condition of terrestrial ecosystems in the border area (cf. Tikkanen and Niemelä 1995, Aamlid *et al*. 2000, Yoccoz *et al*. 2001). The Interreg IIIA Kolarctic project "Development and implementation of an environmental monitoring and assessment program in the joint Finnish, Norwegian and Russian border area" was carried out during the period 2004–2006 (Stebel *et al*. 2007). This project provided a new baseline by updating long-term data series, as well as by integrating and harmonising the approaches used in previous monitoring activities. By joining forces trilaterally the effects of pollution could be studied over an exceptionally large area, ranging from heavily polluted to almost unaffected areas, which is crucial for drawing sound conclusions about the effects of pollution on e.g. terrestrial ecosystems. In this paper we address the hypothesis that there is a differentiation in the impact and geographical distribution of the effects of pollutants on epiphytic lichens, ground vegetation and the growth and crown condition of Scots pine due to the different sensitivity of these plant groups to pollution. The results are used to draw up recommendations for future monitoring activities aimed at evaluating the effects of the ongoing modernisation of the smelter in Nikel on the vegetation in the region.

Material and methods

Study area and plot networks

The study area (69–70°N, 29–32°E) is located close to the Arctic tree line in Scots pine and birch forests, and encompasses the smelter in Nikel, the roasting plant in Zapolyarnyy and the surrounding affected area, as well as less affected areas to the west and south (Fig. 1). The codes R, N and F denote plots in Russia, Norway and Finland, respectively, and the numbers denote increasing distance from Nikel (Fig. 1 and Table

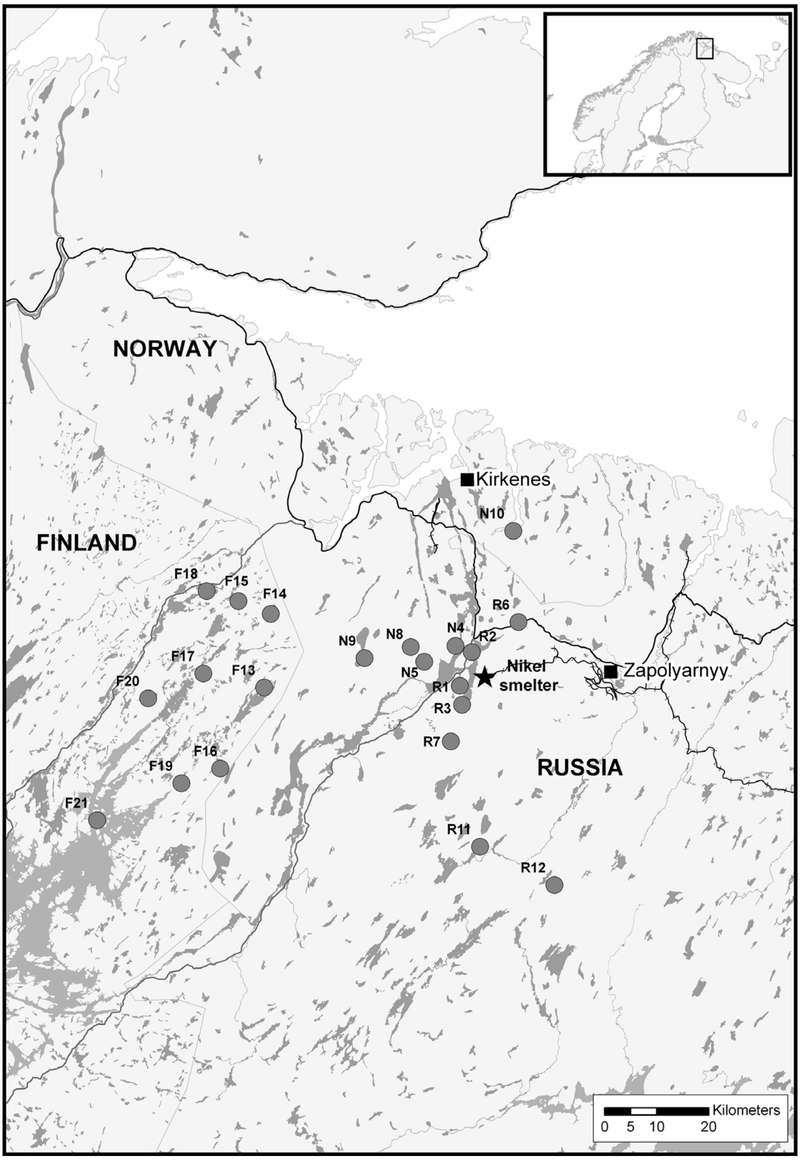

Fig. 1. Location of the monitoring plots.

1). The area is relatively flat, with hills of up to 450 m a.s.l. Precambrian bedrock partly covered by coarse-textured podzolic till dominates the area (Koptsik *et al*. 1999). Hard and infertile gneissic and granitic bedrocks are dominant in the south and north, whereas richer and more easily weathered bedrocks cover large areas to the southeast of Nikel, in the central part of the area (Petsamo formation), and in the uppermost part of the Pasvik Valley (Reimann *et al*. 1998). The Barents Sea creates a climatic gradient with a coastal climate in the north, and an increasingly continental climate on moving towards the south. The annual mean temperature close to the sea (Kirkenes) is 0.2 °C, while it is −1.1 °C in the southern part of the Pasvik Valley, about 100 km from the coast. The annual normal precipitation varies from 340–500 mm. The snow cover is normally formed in mid December and lasts to May (Aune 1993, Førland 1993). The prevailing wind direction in the Nikel area is from the south-southwest (Bekkestad *et al*. 1995, Hagen *et al*. 2006). Reindeer grazing pressure in the Norwegian and Finnish part of the study area is

Table 1. Plot codes, plot characteristics and monitored parameters. Sequence of plots is arranged in order of increasing distance from the Nikel smelter. The old plot codes refer to the codes used in Aamlid *et al*. (2000), Yoccoz *et al*. (2001) and Stebel *et al*. (2007), and have been included to make the comparison easier. Determination of the exact age of the stands on some of the Finnish plots was problematic because all of the stands were naturally regenerated and have never been managed since.

Plot characteristics								Monitored parameters					
Plot codes	Old plot codes	Distance from Nikel smelter (km)	Altitude (m a.s.l.)	Original project[1]	Dominating tree	Average stand age in 2004 (years)	Vegetation type (Påhlsson 1994)	Crown condition	Stand growth	Epiphytic lichens	Ground vegetation	Deposition	Humus chemistry
R1	RUS2	5.1	26	1	Scots pine	52	*Pinus–Vaccinium vitis-idaea*	X	X	Birch, Scots pine	X		X
R2	RUS1	5.2	49	1	Scots pine	52	*Pinus–Vaccinium vitis-idaea*	X	X	Birch, Scots pine	X	X	X
R3	S03	7.0	22	2	Birch		*Betula–Empetrum–Cladonia*			Birch	X		X
N4	PC	8.1	70	1	Scots pine	60	*Pinus–Vaccinium vitis-idaea*	X	X		X	X	X
N5	PD	11.9	50	1	Scots pine	45	*Pinus–Cladonia*	X	X		X		X
R6	N06	12.3	105	2	Birch		*Betula–Vaccinium–Deschampsia*			Birch	X		X
R7	S05	14.1	131	2	Birch		*Betula–Empetrum–Cladonia*			Birch	X		X
N8	PB	15.3	90	1	Scots pine	56	*Pinus–Vaccinium vitis-idaea*	X	X	Birch	X		X
N9	PA	23.3	103	1	Scots pine	50	*Pinus–Vaccinium vitis-idaea*	X	X	Birch	X		X
N10	N11	28.4	47	2	Birch		*Betula–Vaccinium–Deschampsia*			Birch	X	X	X
R11	S10	32.8	191	2	Birch		*Betula–Empetrum–Cladonia*			Birch	X		X
R12	RUS0	42.2	193	1	Scots pine	67	*Pinus–Vaccinium vitis-idaea*	X	X	Birch, Scots pine	X	X	X
F13	F4	42.3	177	3	Scots pine	~200	*Pinus–Vaccinium vitis-idaea*	X		Scots pine	X		X
F14	F1	42.7	100	3	Scots pine	200+	*Pinus–Cladonia*	X		Scots pine	X		X
F15	F2	49.4	120	3	Scots pine	200–300	*Pinus–Vaccinium vitis-idaea*	X			X		X
F16	F7	53.7	173	3	Scots pine	235	*Pinus–Vaccinium vitis-idaea*	X		Scots pine	X		X
F17	F5	54.0	172	3	Scots pine	185	*Pinus–Cladonia*	X		Scots pine	X		X
F18	F3	55.8	100	3	Scots pine	~200	*Pinus–Vaccinium vitis-idaea*	X		Scots pine	X	X	X
F19	F8	61.7	160	3	Scots pine	188	*Pinus–Vaccinium vitis-idaea*	X		Scots pine	X		X
F20	F6	64.7	140	3	Scots pine	192	*Pinus–Vaccinium vitis-idaea*	X			X		X
F21	F9	79.3	120	3	Scots pine	191	*Pinus–Vaccinium vitis-idaea*	X		Scots pine	X		X

[1] Skogforsk-NINA-VNIIPRIRODA-IGCE project (Aamlid *et al*. 2000). 2: NINA-NGU-INEP-METLA monitoring network (Yoccoz *et al*. 2001). 3: Finnish Lapland Damage Project (Tikkanen and Niemelä 1995).

low, 1.1–1.3 reindeer km^{-2} in Norway and about 1.6 reindeer km^{-2} in Finland. For comparison, the density of reindeer in West Finnmark, Norway, is 9–10 reindeers km^{-2}. There is no reindeer husbandry practiced in the Russian part of the border area (Nieminen 2004, The Directorate for Reindeer Husbandry 2007).

Twenty one plots were selected from three different monitoring projects with a different monitoring design, covering a gradient from heavily polluted areas to those with almost no pollution impact. The eight Norwegian and Russian plots, established in boreal Scots pine forest as a part of the Skogforsk-NINA-VNIIPRI-RODA-IGCE project (Aamlid *et al*. 2000), are distributed along an east–west transect (N9, N8, N5, N4, R2, R1), with a remote plot to the south-east (R12) that is the least affected by air pollution (Table 1 and Fig. 1). These plots consist of a rectangular 25 m × 40 m area for the assessment of tree vitality, forest growth and ground vegetation. Analysis of epiphytic lichen vegetation on birch and Scots pine stems was performed in the buffer zone surrounding the plot. The ground vegetation was analysed in 2004 on ten 1 m × 1 m quadrates within each of the Norwegian plots, randomly selected from the original 20 established quadrates. All 20 quadrates were used on the Russian plots.

The five plots selected from the NINA-NGU-INEP-METLA monitoring network (R3, R6, R7, N10, R11) were established in birch forest, and are distributed along a north–south transect (Table 1 and Fig. 1). Each plot consists of five sub-plots arranged in a cross, with one central and four adjacent subplots 10 m from the central subplot (Yoccoz *et al*. 2001). Each subplot is 15 m × 15 m and the distance from the centre subplot to the adjacent subplots centres is 25 m. Assessments of epiphytic lichen cover were made within the subplots, and the ground vegetation was analysed within 1 m × 1 m quadrates located in the centre of each subplot, giving five quadrates per plot.

The nine plot clusters selected from the Finnish Lapland Damage Project (F13, F14, F15, F16, F17, F18, F19, F20, F21) were all established in Scots pine forest (Tikkanen and Niemelä 1995) (Table 1 and Fig. 1). Each cluster consists of 3–4 circular subplots. One subplot was selected as a sample plot to represent the ground vegetation of the whole cluster. The size of the subplot is 300 m^2, with a radius of 9.8 m. A total of 7–12 quadrates of 1 m × 1 m were systematically established along two transects within the subplot for the ground vegetation assessments.

Sampling and chemical analysis of precipitation

Bulk deposition was monitored on plots in Norway, Russia and Finland for a period of one year (Table 2). The plots in Norway and Finland were established at the beginning of June 2004. For logistical reasons the plot in Russia was established at the beginning of October 2004. The equipment for collecting the rain and snow samples was identical on all the plots, and was based on the design used in Finland as a part of the Forest Focus/ICP Forest deposition monitoring programme (http://www.icp-forests.org/pdf/Chapt6_compl2006.pdf). 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. The collectors were emptied at 4-week

Table 2. Annual precipitation (mm), average pH and deposition of metals, sulphate, ammonium, nitrate and chloride (mg m^{-2} year^{-1}) in bulk deposition at plots in Russia, Norway and Finland in 2004–2005. Sequence of plots is arranged in order of increasing distance from the Nikel smelter.

Plot	Precip.	pH	Cu	Ni	SO_4-S	Zn	Fe	Al	Na	Cl	Ca	Mg	K	NO_3-N	NH_4-N
R2	461	4.62	20.9	17.3	102	4.0	14.0	6.3	414	898	70.7	73.2	73.7	7.1	51.3
N4	722	4.94	24.4	27.3	355	8.6	16.5	9.8	517	1686	74.3	104	73.7	57.0	60.5
N10	678	4.91	10.0	7.8	331	5.8	5.6	10.5	763	2188	86.8	123	66.9	61.6	52.7
R12	423	4.51	1.5	0.9	53	4.8	3.7	5.7	130	316	24.7	19.6	22.2	8.6	54.4
F18	485	4.95	1.7	2.7	103	6.2	1.0	7.3	175	306	23.4	23.5	27.3	38.4	28.8

intervals. During the snowfree period all the sample collectors were bulked on site to give one composite sample for each plot. The total volume of the bulked samples was recorded (determined by weighing) in the field, and a sub-sample 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.

Because the sampling period was not exactly one year, the results for annual deposition were adjusted accordingly. pH was measured on the samples and, after filtering through 0.45 um filters, the Cu, Ni, Zn, Fe, Al, Na, Ca, Mg and K concentrations were determined by inductively coupled plasma atomic emission spectrometry (ICP/AES), and the SO_4-S, Cl, NO_3-N and NH_4-N concentrations by ion chromatography.

Assessment of epiphytic lichens

Assessment of the epiphytic lichen cover was carried out on plots with birch and Scots pine on ten randomly chosen stems with a dbh > 5 cm (dbh = diameter at breast height 1.3 m above the ground) on each plot (Table 1). The lichen cover was recorded at four heights on the stems: 135 cm, 150 cm, 165 cm and 180 cm above the ground level by using a simple measuring tape with a marker at each centimetre (Aamlid *et al.* 2000). Starting from north, the number of centimetre markers covering a single lichen species was recorded for each height. Percentage lichen cover on each plot was calculated by dividing the total lichen cover on the circumference at each height, and then calculating the average for each stem and plot. Estimation of correlation coefficients was applied to evaluate the relationship between the lichen cover and the log transformed distance from the pollution source. The log transformed distance for Scots pine did not follow normal distribution, and Spearman's rank correlation coefficient was estimated for this data set.

Ground vegetation assessments and environmental variables

Two hundred and twelve quadrates distributed on 21 plots were analysed to assess the diversity and abundance of lichens, bryophytes and vascular plants in 2004 (45 quadrates from Norway, 80 from Russia and 87 from Finland). In each quadrate, the relative cover of each species was estimated together with the cover of litter, stones, bare ground and the height and the relative cover of the shrub and tree layers above the quadrates. Species covering less than 1% were given the value of 1%. Taxonomic nomenclature follows Lid and Lid (2005) for vascular plants, Frisvoll *et al.* (1995) for bryophytes, and Santesson *et al.* (2004) for lichens.

The average cover of stones, bare ground, shrub and tree layers per plot were estimated as an average of the assessments within the 1 m × 1 m quadrates and used as environmental variables to explain the variation in ground vegetation. Extrapolated climatic data from WorldClim (Hijmans *et al.* 2005), with a spatial resolution of one square kilometre, were used as climatic explanatory variables, together with the log transformed distance from the pollution source, altitude of the plots and chemical data from the organic soil layer. The concentration of Cu and Ni in the humus layer was used as an indirect pollution explanatory variable owing to the lack of any direct measurements of the pollution impact.

Statistical analysis of ground vegetation and environmental variables

The variation in species composition in the total dataset of 212 quadrates was analysed with indirect gradient analysis (ordination) in terms of detrended correspondence analysis DCA (Hill 1979, Hill and Gauch 1980). This method describes major gradients using species abundances irrespective of any environmental variable. 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, using average species abundance data per plot and variables representing the plots. Unimodal response models (DCA and CCA) were chosen since the length of the vegetation gradient was more than 2.0 standard deviation units, as recommended by ter Braak and Prentice (1998).

The gradient analyses were performed with CANOCO 4.1 (ter Braak and Smilauer 2002). Rare species were "downweighted" in the DCA and the CCA analyses by the standard procedure in the programme. The species data were log-transformed in the DCA analysis due to a very high range of abundance values (1%–100%). Plot R6 was given the weight of 0.1 in the CCA analysis due to its occurrence as an "outlier" in a standard CCA. Only those variables which were found to be statistically significant correlated to the vegetation gradients in the unrestricted Monte Carlo permutation tests with 499 random permutations were used in the final CCA.

Crown condition and stand growth

The tree measurements included assessment of crown density, crown colour, and height and diameter growth. All trees with a dbh > 5 cm on each plot were included. Crown density was assessed on Scots pine, with reference to a normally dense crown for trees in the region (Aamlid and Horntvedt 1997, Aamlid *et al*. 2000). The assessments were carried out by trained observers using binoculars, and the trees were inspected from different sides at a distance of about one tree length. Only the upper two thirds of the tree crown were assessed, and the crown density was estimated in 1% classes. Mechanical damage arising from snow break, wiping etc was excluded. Crown colour was estimated using the ICP Forest classes (http://www.icp-forests.org/pdf/Chapt2_compl06.pdf); class 0 = normal green, class 1 = slight yellow, class 2 = moderate yellow, class 3 = strong yellow. Only vigorous trees, non-suppressed by neighbouring trees, were included in the calculations of tree vitality. In Finland, Norway and Russia 28–41, 40–83 and 40–88 non-suppressed Scots pine trees, respectively, were available for the assessment of crown condition on each monitoring plot. Simple linear regression was used to estimate the relationship between crown density and growth parameters in Scots pine at the individual tree level.

Tree height was measured digitally (Vertex III, Hagløf, Sweden AB), and stem circumference was measured 1.3 m above ground level to an accuracy of 1 mm. The position at the stem was clearly marked to ensure repeated measurements at the same place in the future. Tree volume was calculated according to the volume functions of Brantseg (1967). The increase in tree height, stem circumference and tree volume were calculated by dividing the data from 2004 by the 1998 data. Data from 1998 were not available from Finland, and growth was thus only reported for the Norwegian and Russian Scots pine plots.

Sampling and chemical analysis of the humus layer

Twenty sub-samples of the organic layer (excluding the litter layer) were collected in a 3 m × 4 m grid on each plot, and then pooled. The sampling took place close to the quadrates for the vegetation analysis. pH was measured in an aqueous slurry, total carbon and nitrogen on a CHN analyser, and total phosphorous, copper and nickel by ICP/AES following acid digestion in a microwave oven.

All the field work associated with the ground vegetation assessments, crown condition and stand growth, epiphytic lichens, and collection of humus samples was performed during the first two weeks of August 2004.

Results

Deposition

In 2004–2005, the annual precipitation on the monitoring plots in Russia and Finland ranged between 420–485 mm (Table 2). On the two plots in Norway, which are the closest to the sea, the annual precipitation was 678 and 722 mm. The bulk deposition of sulphate was relatively high on these plots (331 and 355 mg SO_4-S m^{-2} year^{-1}) (Table 2), while on all the other plots sulphate deposition was low (53–103 mg SO_4-S m^{-2} year^{-1}).

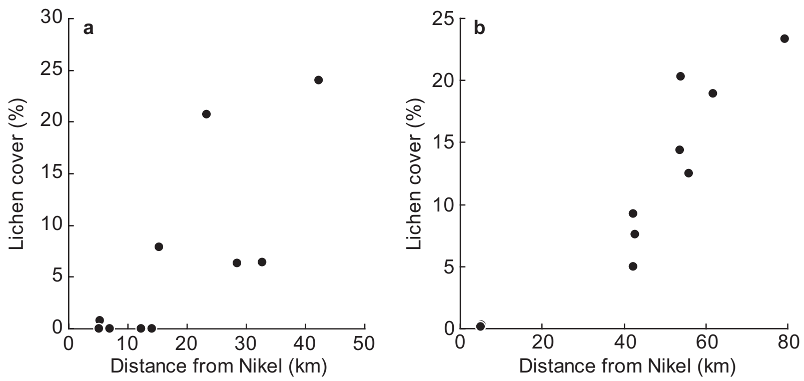

Fig. 2. Total lichen cover on (**a**) birch (*Betula pubescens*) and (**b**) pine (*Pinus sylvestris*) as a function of distance from Nikel.

Similar deposition peaks also occurred for Na, Cl and Mg at the Norwegian plots. The plots received sulphate from two sources: the smelting and roasting industry in Nikel and Zapolyarnyy, respectively (gaseous SO_2 and SO_4^{2-}), and sulphate in aerosols from the sea (e.g. as $MgSO_4$). The average deposition of Cu, Ni, and Fe was substantially elevated on the plots north of Nikel (Table 2 and Fig. 1). The temporal variation in deposition around Nikel is characterised by occasional peaks that vary in synchrony for the main pollutants. At plot N4 the four-week averages for Cu, Ni and sulphate varied from about zero to 0.144 mg l^{-1}, 0.141 mg l^{-1} and 1.25 mg l^{-1}, respectively.

Epiphytic lichens

The Finnish and Russian pine plots were all species-poor. The dark pendant lichen *Bryoria fuscescens*, possibly also including some thalli of other *Bryoria* species, was by far the most common lichen on the pine trees. On the Finnish plots it was recorded four times as often as the second most common lichen, the small-foliose *Imshaugia aleurites*. The plots at a distance of about 5 km from Nikel had the lowest lichen abundance with less than 1% total cover, and the cover was less than 10% at a distance of 42–43 km. The plots farther away from Nikel had up to 23.4% total lichen cover. Thus, there was a strong relationship between the distance to Nikel and the lichen cover on the pine trees ($r^2 = 0.86$) (Fig. 2).

The Russian and Norwegian plots with birch were also species-poor, and *Parmelia sulcata* was by far the most common species on birch with about 60% of all records (Fig. 2). Lichens were absent on four plots situated at distances between 5 and 14 km from Nikel. On the plot closest to Nikel a few minute thalli were recorded, giving an overall relative cover of 0.8%. The remaining plots situated between 15 and 79 km from Nikel had between 6% and 24% relative cover. This gradient resulted in a significant correlation between the lichen cover and distance from Nikel ($r^2 = 0.52$) (Fig. 2).

Vegetation types

All the Finnish plots, the Norwegian plots N4, N5, N8 and N9 and the Russian plots R1, R2 and R12 are situated in northern boreal Scots pine forests (Fig. 1 and Table 1). The ground vegetation of the pine forest plots was generally rich in lichens with species such as *Cladonia arbuscula*, *C. crispata*, *C. gracilis*, *C. sulphurina*, *C. rangiferina*, *C. stellaris*, *C. uncialis*, *C. coccifera*, *C. chlorophaea* and *C. fimbriata*. The most common bryophytes were oligotrophic mosses such as *Dicranum fuscescens*, *D. scoparium*, *Pleurozium schreberii* and *Polytricum juniperinum*. Liverworts, mainly *Barbilophozia* spp. and *Lophozia* spp. were also common. The most abundant dwarf shrubs were *Empetrum nigrum* ssp. *hermaproditum*, *Rhododendron tomentosum* (syn. *Ledum palustre*), *Vaccinium myrtillus* and *V. vitis-idaea*. Herbs and grasses had a sparse distribution, except *Avenella flexuosa* (syn. *Deschampsia flexuosa*), which occurred on most of the plots.

Two of the Finnish plots (F14 and F17) and the Norwegian plot N5 had a species composition

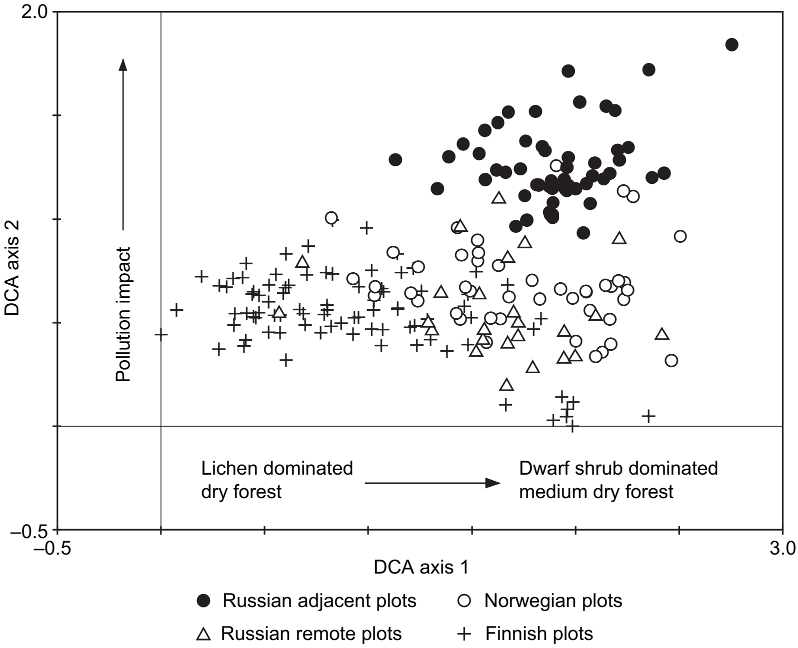

Fig. 3. Detrended correspondence analysis (DCA) diagram of 212 quadrates, axes 1 and 2, with interpreted environmental gradients. "Russian remote plots" refer to R11 and R12. (From Stebel *et al.* 2007, adapted by the authors of this paper).

similar to the dry, oligotrophic vegetation type of "*Pinus sylvestris–Cladonia* spp. type" described in Påhlsson (1994), which is comparable to the "*Cladonia* woodland, *Cladonia–Pinus sylvestris* subtype" in Fremstad (1997). The rest of the Finnish plots, the Norwegian plots N4, N8 and N9 and the Russian remote plot R12 were more dominated by dwarf shrubs and thus resembled the relatively dry "*Pinus sylvestris–Vaccinium vitis-idaea* type" (Påhlsson 1994), comparable to the "*Vaccinium-vitis-idaea–Empetrum nigrum* coll. subtype of the *Vaccinium* woodland" (Fremstad 1997). The Russian plots R1 and R2 probably also belong to this vegetation type. However, visible injuries on the vegetation made it difficult to determine their original vegetation type.

The Norwegian plot N10 and the Russian plots R3, R6, R7 and R11 are situated in birch forests. These plots were characterized by almost the same species as the plots in the pine forests. However, in general, the birch forest plots had a lower cover of lichens, and additional species such as *Chamaepericlymenum suecicum* (syn. *Cornus suecica*), *Orthilia secunda*, *Pedicularis lapponica*, and *Trientalis europaea* indicated slightly more mesic vegetation.

Plot N10, rich in *Vaccinium myrtillus*, and partly also R6, resembles the "*Betula pubescens* ssp. *czerepanovii–Vaccinium myrtillus–Deschampsia flexuosa* type" (Påhlsson 1994), comparable to the "*Vaccinium myrtillus–Empetrum nigrum* coll. subtype of the bilberry woodland" (Fremstad 1997) on slightly mesic and humid soil. Plot R6 was also characterized by the low fern *Gymnocarpium dryopteris* and *Solidago virgaurea*. The Russian birch plots R3, R7 and R11 probably belong to the somewhat dryer "*Betula pubsecens* ssp. *czerepanovii–Empetrum hermaphroditum-Cladonia* spp. type" (Påhlsson 1994), comparable to the "*Vaccinium-vitis-idaea–Empetrum nigrum* coll. subtype of the *Vaccinium* woodland" (Fremstad 1997).

Gradients in species composition of the ground vegetation

The DCA ordination of the total of 212 quadrates showed a gradient from dry, lichen-dominated forests to medium dry, dwarf shrub dominated forests along the first ordination axis, and thus reflected the main gradient in the above described vegetation types (Fig. 3). However, the species composition of the Russian plots in the vicinity of the Nikel smelter (filled circles) were very different from the vegetation on the

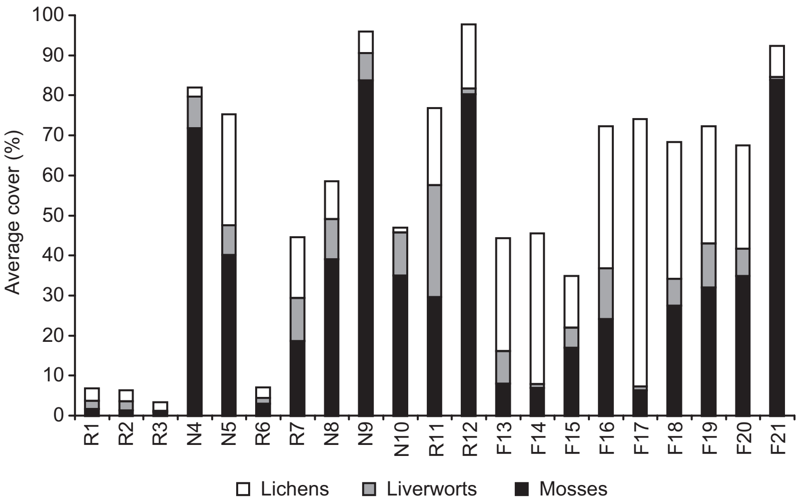

Fig. 4. Average percentage cover of bryophytes and epigeic lichens on the monitoring plots. Sequence of plots (left to right) arranged in order of increasing distance from the Nikel smelter.

other plots, as shown by their distinct separation on the high DCA axis 2 scores. These differences were mainly related to the occurrence and abundance of bryophytes and epigeic lichens in the ground layer (Fig. 4). Mosses and liverworts were almost absent on the Russian plots close to the Nikel smelter. Some bryophyte species (*Dicranum* spp., *Hylocomium splendens*, *Plagiothecium laetum*) were not found on these plots at all. The Finnish plots had, in general, a medium bryophyte cover, while the ground layer on the Norwegian and the Russian plots farthest away from Nikel were dominated by mosses and partly by liverworts.

The lichen cover was very sparse on plots close to the pollution source (Fig. 4), and mainly comprised pioneer cup lichens (e.g. *Cladonia chlorophaea*, *C. botrytis*, *C. gracilis*, *C. pyxidata*, *C. sulphurina*). The cover was even less than indicated, because species covering less than 1% were given the value of 1%. The Finnish plots and the Norwegian plot N5 had the highest abundance of epigeic lichens, with a dominance of reindeer lichens (*Cladonia arbuscula*, *C. mitis*, *C. rangiferina* and *C. stellaris*) in additions to species of *Cetraria* and *Peltigera*. Lichens were also common on the most remote Russian plots.

The average number of species per 1 m × 1 m quadrate was lowest on the plots close to the Nikel smelter due to the relatively few species of mosses and lichens (Fig. 5). The number of dwarf shrubs (including all woody species below 50 cm, e.g. *Empetrum nigrum* ssp. *hermaphroditum*, *Rhododendron tomentosum*, *Vaccinium myrtillus*, *V. vitis-idaea*) was relatively constant on all the plots. In general, the number of herbs and grasses was lowest on the Finnish plots, which also had the highest number of lichen species.

Relationships between species composition and environmental variables

The CCA showed that the most important variables explaining the variation in species composition of the ground vegetation were total phosphorous in the humus layer (P), humus pH, total copper concentration in the humus (Cu), distance from the pollution source (Distance), carbon/nitrogen ratio of the humus (C/N), total nickel concentration in the humus (Ni), mean annual temperature (Mean year temp) and the litter cover on the ground (Litter), in slightly decreasing importance, as shown by the length of the biplot arrows (Fig. 6). Precipitation, altitude, tree and shrub cover and the cover of stone and bare ground were not found to be statistically significant related to the species variation.

A partial constrained correspondence analysis (Borcard *et al*. 1992) with the “pollution variables” Ni and Cu in the humus layer as the environmental variables and pH, P, C/N, litter and mean annual temperature as covariables showed

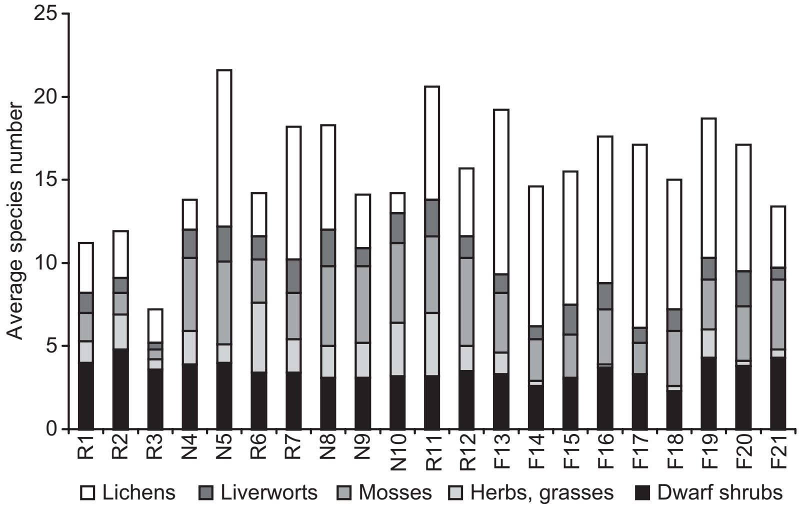

Fig. 5. Average number of plant species per 1 m^2 in different plant groups on the monitoring plots. Sequence of plots (left to right) arranged in order of increasing distance from the Nikel smelter.

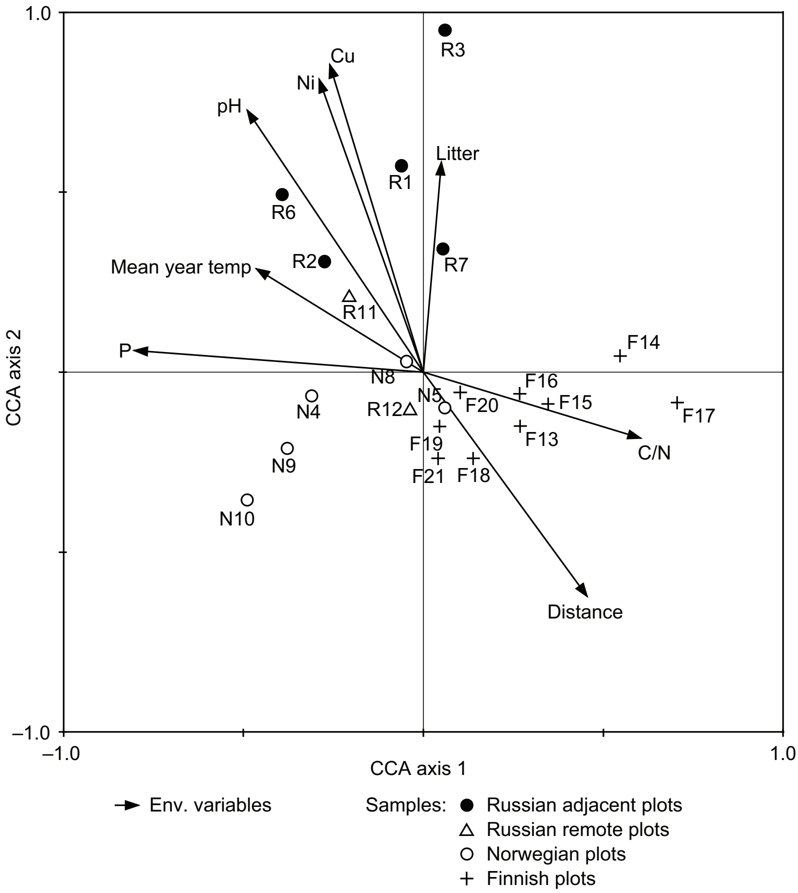

Fig. 6. Canonical correspondence analysis (CCA) diagram of species abundance data and environmental variables from 21 plots, axis 1 and axis 2. Environmental variables represented by biplot arrows. "Russian remote plots" refer to R11 and R12.

that Ni was significantly related ($p = 0.04$) to the variation in species composition, when the variation explained by the other variables had been taken into account.

The ground vegetation on the Russian plots close to Nikel was positively correlated to plots with medium to high total P concentrations, relatively high pH, high total Cu and Ni concentrations and low C/N values in the humus, shown by the direction of the biplot arrows (Fig. 6). In general, these plots had the highest litter cover and they were all situated in areas with relatively high mean annual temperatures. The plots which were characterized by high lichen cover (Fig. 4) had the highest C/N ratios, lowest pH and total P, Cu and Ni concentrations in the humus layer. Especially the Finnish plots showed a relationship with low mean annual temperatures. Most Norwegian plots were characterized by vegetation commonly found on sites with medium and high humus P concentrations and medium values of pH, C/N ratio and Ni.

Crown condition

Discoloration in Scots pine was not recorded in the study area. The crown density was high and stable across the two assessments on the moderately polluted Norwegian plots as compared to the heavily polluted plots in Russia, and the remote plots at a distance of more than 42 km from Nikel (Table 3). The average stand age on the Finnish plots were, however, considerably higher than those on the plots in Norway and Russia (Table 1).

Stand growth of Scots pine was calculated as percentage increase in the increment of height, basal area and volume between 1998 and 2004 (Table 3). The highest increase in basal area was associated with the plots close to the smelter in Nikel, and the lowest with a remote plot (R12). The difference between the Norwegian plots was small and unrelated to distance from the smelter. The height increment was relatively even along the gradient, except for the comparably low increments at two plots situated at each end of the pollution gradient (R2, R12). As the volume increment was calculated from the increment in basal area and height, the highest volume increment was found close to the smelter, and the lowest on the remotest plot. The correlation between crown density and growth was significant ($p < 0.0001$), but moderate ($r^2 \leq 0.14$).

Discussion

The results of this study show that industrial pollution is still affecting the vegetation in the border area. The most pronounced effects are associated with epiphytic lichens, which are known to be very sensitive to SO_2 emissions in this area and elsewhere (Hawksworth and Rose 1976, Tarhanen *et al*. 2000). Plots in the vicinity of Nikel had no or a very modest epiphytic lichen cover, whereas there was an increase in lichen cover with increasing distance from the smelter on both pine and birch stems (Fig. 2).

The SO_2 concentration generally decreases with increasing distance from the Nikel smelter, with the highest concentrations in the southwest-

Table 3. Crown density and growth increase in Scots pine. The values for the Finnish plots are means of three adjacent plots. Different single letters (growth increase) show significant differences between plots at $p < 0.05$, two letters (e.g. ab) implie no significant difference *vs*. values with the individual single letters (e.g. a and b). Sequence of plots is arranged in order of increasing distance from the Nikel smelter.

Plot	Crown density (%)		Growth increase (%) 1998–2004		
	2004	2005	Basal area	Tree height	Volume
R1	82.1		34.4^{b}	15.9^{a}	49.1^{b}
R2	76.8		38.4^{a}	12.1^{b}	56.1^{a}
N4	94.3	93.6	23.6^{cd}	14.5^{a}	36.2^{c}
N5	93.9	93.0	21.7^{d}	14.7^{a}	34.5^{c}
N8	92.9	92.3	25.4^{cd}	14.0^{ab}	36.0^{c}
N9	93.4	93.8	27.3^{c}	15.7^{a}	39.9^{c}
R12	57.9		10.6^{e}	7.0^{c}	16.5^{d}
F14, 15, 18		74.5			
F13, 17, 20		79.6			
F16, 19, 21		85.3			

ern-northeastern sectors of the pollution source (Bekkestad *et al.* 1995, Hagen *et al.* 2000, Stebel *et al.* 2007). Although the SO_2 emissions from the Petchenganickel combine have been reduced to ca. one third over the last three decades, annual emissions still amount to about 120 000 tonnes (Henriksen *et al.* 1997, Milyaev and Yasenskij 2004). The deposition of Ni, Cu and Fe were strongly elevated (Table 2). However, on some of the plots (e.g. in Finland), the Cu and Ni concentrations were extremely low, and in many cases below the limit of quantification of the analytical equipment. As a result, there was a clear spatial gradient in the deposition. The decline in heavy metal concentrations with distance from Nikel is more abrupt than the reduction of SO_2 concentrations, because the heavy metals are present as particles in aerosols (Bekkestad *et al.* 1995, Bjerke *et al.* 2006). Accordingly, the harmful effect of SO_2 on epiphytic lichens may occur at greater distances from Nikel than indicated by the low heavy metal concentrations in deposition in the periphery of the study area (Table 2). Owing to the climatic heterogeneity, it is difficult to assess the geographical area in which the cover of epiphytic lichens is reduced by the emissions, beyond the epiphytic desert zone. Two distant plots at 28 km and 42 km from Nikel had a relatively low lichen cover; one was at a relatively high altitude south of Nikel (R12), and the other to the north, close to the Barents Sea (N10). It is likely that the severe climate, rather than air pollution, was the most important factor limiting the epiphytic lichen vegetation on these two plots. Similar conclusions concerning the effect of climate on epiphytic lichens in this region have also been drawn by Aamlid and Skogheim (2001) and Bjerke *et al.* (2006). In our study the environmental conditions are probably more variable across the birch plots than pine plots, since some of the birch plots are situated further north towards the coast. For instance, the high deposition of SO_4, Na, Cl, and Mg on the plots closest to the sea (e.g. N10, Table 2) reflects comparably high precipitation rates and the high concentrations of these compounds in sea water (Dring 1986). In addition, the temperatures at the coast are higher during winter and lower during summer than further inland (Aune 1993). All the Norwegian plots are situated in an area which was considered to be an epiphytic lichen desert in 1982–1983 (Bruteig 1984). Comparison with data from the first survey (1995–1998, Aamlid *et al.* 2000) shows that the lichen cover has increased notably on birch on the least polluted plots west of Nikel. This indicates that the reduction in the SO_2 emissions has been sufficient for lichen recolonisation. However, our data (Fig. 2) suggest that the impact area extends at least 20 km to the west of Nikel and probably even further to the north because of the predominant wind directions from south-southwest (cf. Aamlid and Skogheim 2001, Hagen *et al.* 2006). Interestingly, this corresponds relatively well to the area around Nikel delimited by the modelled isoline for 10 μg m^{-3} SO_2 (Bekkestad *et al.* 1995), a pollution level regarded as a critical mean level for vulnerable lichens (UN ECE 1993).

The main variation in the ground vegetation within the monitoring network was related to differences in natural environmental variables such as climate and soil conditions. The relatively dry, naturally acidic soils (low pH) with low nutrient availability (high C/N ratio) and limited grazing impact on the Finnish plots favour lichen-dominated ground vegetation, while higher pH values and a lower C/N ratio in the humus layer of the Norwegian plots (except N5) may indicate slightly more fertile soils favouring mosses, herbs and grasses (Fig. 5). However, although the density of semi-domestic reindeers is low and at about the same level in the Norwegian and Finnish part of the monitoring area (Nieminen 2004, The Directorate for Reindeer Husbandry 2007), local differences in grazing pressure might affect the species composition of the ground vegetation. The vegetation on the Finnish plots and the remote Russian plots might also be influenced by the more continental climate with generally lower annual mean temperatures and lower winter temperatures (Hijmans *et al.* 2005), which favour lichen-dominated ground vegetation (Haapasaari 1988).

On the Russian side of the border area, however, there are no semi-domestic reindeer (Jernsletten and Klokov 2002, Tømmervik *et al.* 2003). The plots close to Nikel should therefore potentially have as high a lichen cover, if not affected by air pollution, as the remote Russian plots. However, the lichen cover close to Nikel is generally lower than that on most of the other monitoring plots (Fig. 4). Elevated levels of SO_2 and heavy metals are toxic to lichens and bryophytes, especially bio-available Cu in mosses (Shaw 1990, Salemaa *et al.* 2004), which may contribute to their lower coverage and diversity in the vicinity of the Nikel smelter (Figs. 4 and 5). Moreover, the total Ni and Cu concentrations in the humus layer decreased with increasing distance from the pollution source (Fig. 6), and the concentrations were significantly correlated with the change in species composition on moving away from the smelter, even when the variation related to natural environmental variables was taken into account. This strongly suggests that the emissions affect both the cover and richness of epigeic lichens and bryophytes in the vicinity of the Nikel smelter (Figs. 4 and 5). A reduction in epigeic lichens and bryophytes has previously been reported in the same area by Tømmervik *et al.* (1998, 2003), Chernenkova and Kuperman (1999), Aarrestad and Aamlid (1999) and Aamlid *et al.* (2000) as an effect of air pollution from Nikel and Zapolyarnyy.

The pollution gradients, however, were not strictly related to the distance from the pollution source. The reduced bryophyte and lichen cover was clearly evident at the Russian plot R6 12.3 km to the north-east of the Nikel smelter, while there was no indication of any pollution effect on the Norwegian plot N5 11.9 km west of the smelter (Fig. 6). This can be explained on the basis of the above-mentioned pollution corridor running mainly in a southwest-northeast direction from the smelter, which is probably related to the prevailing wind directions in the area (Bekkestad *et al.* 1995, Hagen *et al.* 2006, Stebel *et al.* 2007).

One fact that possibly may have an impact on the species composition of the ground vegetation on the Russian plots is the high frequency of uncontrolled, man-made forest fires in the Russian area (Knjazev and Nikonov 2003, Tømmervik *et al.* 2003, Knjazev and Isaeva 2006, Knjazev and Sukhareva 2007). Although the Russian plots were selected as not being influenced by recent fires, we do not know the exact fire history of these plots.

Degradation of the ground vegetation leads to increased litter accumulation, and the deposition of air pollutants may lower the mineralization and decomposition rates of the litter due to reduced microbiological activity (Fritze 1989). The accumulation of litter will tend to suppress recolonization and plant growth due to the unfavourable temperature and moisture conditions (Salemaa *et al.* 2001, Kozlov and Zvereva 2007b). Soil pH might also be reduced through the effects of sulphur deposition, as reported by Lukina and Nikonov (1995) in the Nikel area, and changes in soil acidity may subsequently lead to changes in the species composition.

Thus, even though the main vegetation gradients in the joint Finnish–Norwegian–Russian monitoring network can be partly explained by several natural factors (e.g. climate, humidity, soil fertility) and human disturbance (e.g. reindeer grazing, forest fires), there is no doubt that the emissions of SO_2 and heavy metals from the Nikel smelter have and are still affecting the ground flora in the vicinity of the smelter. The main effects are reduced species richness and abundance of the bryophyte and lichen flora, and increased litter accumulation on the forest floor. The dwarf shrubs *Empetrum nigrum* ssp. *hermaphroditum* and *Vaccinium vitis-idaea* seem to be less sensitive to the pollution, as demonstrated earlier (cf. Monni *et al.* 2000, Uhlig *et al.* 2001, Zvereva and Kozlov 2004). These effects are clearly visible at plots close to the smelter in Nikel where many species of mosses, liverworts and lichens have disappeared, while those that have survived have low occurrence and cover values. It is unclear whether pollution has affected the ground vegetation at the Norwegian and Finnish plots. Accordingly, the impact area for ground vegetation appears to be smaller than the area where epiphytic lichens are reduced or absent. This is in agreement with the higher critical annual mean SO_2 estimate for natural vegetation and forests in areas of low temperatures (15 $\mu g\ m^{-3}\ SO_2$) than for epiphytic lichens (10 $\mu g\ m^{-3}\ SO_2$) (UN ECE 1993). Epiphytic lichens situated 135–180 cm above the ground surface are not protected by snow during winter, and could be exposed to air pollution throughout the year. Thus, life history traits may partly explain the higher sensitivity of epiphytic lichens to SO_2.

Our data on crown condition and the growth of pine do not provide conclusive evidence that pollution has affected these parameters. Discoloration of the tree crowns can indicate climatic-related damage, nutrient deficiency or direct SO_2 damage (Merilä *et al*. 1998, Purdon *et al*. 2004), but the crown colour was assessed as normal (i.e. green) on all the plots. There was some variation in the crown density assessments, with high and stable values in Norway and distinctively lower values both in the more and less polluted areas in Russia and Finland, respectively. Sharp changes at country borders due to methodological differences (cf. De Vries *et al*. 2000) are unlikely because harmonisation of the assessments was ensured prior to the fieldwork. The low crown density of the remotest plots may be partly due to the high age of the Finnish stands (Table 1), and attack by *Peridermium pini* (R12), reducing the overall stand vitality. These explanations do not apply to the plots adjacent to the smelter, indicating that the low crown density of these plots could be due to the emissions. A similar conclusion was drawn by Aamlid *et al*. (2000). A relatively strong correlation has been found between crown density and growth in Norway spruce (*Picea abies*) (Solberg 1999). In the present study the correlation between crown density and growth was significant, but moderate, which implies that crown condition has a limited capacity to quantify growth in pine in our data. Despite signs of decreased soil fertility and increased soil acidity in the border area (Lukina and Nikonov 1997, Derome *et al*. 1998, Steinnes *et al*. 2000), there were no indications that this has reduced the growth of pine because the greatest growth increase was associated with the most polluted plots (Table 3). Westman (1974) also obtained variable results concerning the growth of pine in the vicinity of a sulphite plant in Sweden, despite the occurrence of indisputable effects on epiphytic lichens.

In conclusion, the extensive monitoring network composed of three previous networks shows that the terrestrial biota in the Norwegian–Russian–Finnish border area is still severely influenced by industrial air pollution. We found a pronounced differentiation in sensitivity and size of the impact area depending on the vegetation component studied. Epiphytic lichens were most affected, followed by bryophytes and lichens in the ground vegetation. The crown condition of pine may also be reduced close to the Nikel smelter, but there are no indications that crown colour and stand growth were negatively influenced. As renovation of the Nikel smelter is expected to be completed by 2009 (Stebel *et al*. 2007), it is recommended that monitoring should be continued to quantify possible recovery and further effects on the terrestrial ecosystems. It is important to retain the present vegetation components in a future monitoring programme because they represent a gradient in pollution sensitivity. Epiphytic lichens and the species composition of the ground vegetation (especially lichens and bryophytes) may provide a tool for detecting any initial recovery in the forests ecosystems associated with a decrease in the emissions. Although crown condition and the growth of pine do not appear to be sensitive indicators of pollution, a consistent negative effect on these attributes would strongly indicate an unexpected increased pollution impact, or episodes of locally high SO_2 deposition. The assessment of crown condition is a relatively cost-effective measure, and should be undertaken annually on all the plots dominated by pine. Stand growth, epiphytic lichens and the species composition of the ground vegetation should be monitored at 4–5-year intervals on the plots as in the present study, and we recommend that all assessments should be carried out during the first two weeks of August when the ground vegetation is fully developed. The spatial distribution of monitoring plots should be maintained, or even increased, to the east of Nikel.

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