Editors: Eero Tikkanen & Irja Niemelä

Kola Peninsula pollutants and forest ecosystems in Lapland



The Severonikel nickel-copper smelter at Monchegorsk. Photo: Erkki Oksanen.

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Edited by
Eero Tikkanen and Irja Niemelä



Final Report of
The Lapland Forest Damage Project

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Foreword

The news released in the late 1980s about the immense pollution emissions and environmental damage in the Kola Peninsula region of north-western Russia and about the forest damage in Finnish Lapland were causes of concern for the Finnish public. As the conception of Lapland as a non-polluted background area began to crumble, demands for imposing restrictions on the Kola emissions and finding out the causes of forest damage in Lapland began to be voiced. What little information there was available in the late 1980s on the influence of airborne pollutants on the forests of Finnish Lapland was of scattered character. The experiences gained in connection with the national acidification project HAPRO conducted at the time also indicated that our knowledge of the situation in Lapland was inadequate; the final report of the said project proposes further research efforts to be implemented in Finnish Lapland and the Kola Peninsula.

A five-year Lapland Forest Damage Project was launched in May 1989 at the initiative of the Finnish Forest Research Institute (METLA). Four universities and five research institutes participated in the project. All in all, the project has received contributions from fifty leading Finnish environmental scientists specialising in forest research.

The primary goal in the Lapland Forest Damage Project was to make an assessment of the impact on the forests of Finnish Lapland of the pollution emissions from the Kola Peninsula. Secondly, the project aimed to locate and delimit forest damage areas on the Russian side of the border. The third goal was to produce basic scientific knowledge on the environment in Finnish Lapland and the changes taking place in it. The project was funded by Finland's Ministry of Agriculture and Forestry.

The present publication is a compendium of the centrally significant results obtained in the course of the research project in addressing the aforementioned environmental problem and its impact on Finnish Lapland and northern Fennoscandia (northern Norway, Sweden, Finland and the Kola Peninsula) as a whole. The publication is based on the final report of the Lapland Forest Damage Project, published in Finnish in May 1995. The results presented address issues such as the impact on the forests of Finnish Lapland of the emissions of pollutants from the Kola Peninsula, the extent of the forest-death areas, and the expansion of damage zones in the Kola Peninsula, and the present state of health of forests in Finnish Lapland.

The Forest Damage Project has had the effect of expanding and deepening research co-operation among universities and research institutes in Finland. It has created a new kind of atmosphere of co-operation. Also of significance is the initiation of research co-operation between Finnish scientists and their Russian colleagues based in the Kola Peninsula and engaged in environmental research in forestry. The results of these joint research efforts will be published in due course in international scientific series in the fields of environmental science and forest research. The publicity attracted by the environmental problems of the Kola Peninsula and the research focusing on these problems has also led to marked increase in the number and efficiency of air-quality measurement points in Finnish Lapland; in the late 1980s, there were two national measurement stations whereas now the region boasts Finland's densest and best equipped network of six stations measuring the quality of background air. The local people's awareness of and interest in environmental matters has also increased as a result of the Forest Damage Project.

I wish to express my appreciation to the Ministry of Agriculture and Forestry for funding this extensive research entity. I also wish to thank the researchers and assisting personnel involved in the project, including those who participated in the preparation of this publication, for their excellent co-operation. Thanks are also due to the Finnish public for the interest and concern they have shown for the state of health of our forest environment and the alacrity with which they have brought matters to our attention.

Eero Tikkanen,
Lapland Forest Damage Project
Project Manager



Background to the research project and its implementation

Author

Eero Tikkanen

Figure 1. Collecting throughfall and stemflow samples on the intensive sample plot in Kemijärvi. Litter funnels in the background. Photo: Erkki Oksanen.

Background to the research project and its implementation

Prior to the mid-1980s, very little forest damage research related to airborne pollutants had been conducted in Finnish Lapland and what there was was of non-uniform character (Tikkanen 1989, 1991). This state of affairs was partly explained by the general conception of Finnish Lapland as an unpolluted region and of its forests as being healthy and vigorous. As a thought-to-be pollution-free background area, Lapland found use mainly as a source of control material for environmental studies conducted elsewhere. Air quality measurements were attended to at national stations located in Sodankylä and Kevo (Utsjoki) where data was collected on the quality of background air.

It was in connection with the national acidification research project HAPRO (an acronym derived from the programme's name in Finnish meaning The Finnish Acidification Research Programme) in 1985 that the Finnish Forest Research Institute (METLA) launched a project called ILME (an acronym derived from the project's name in Finnish meaning The Effect of Air Pollution on Forest Ecosystems) delving into the impact of airborne pollutants on forests. A network of more than 3 000 permanent sample plots was established during the years 1985 and 1986 in connection with the 8th national forest inventory to enable the vitality and state of health of Finnish forests to be monitored. Based on systematic sampling, this network was made less dense in Lapland (as it was believed to be less polluted than the rest of the country) than in southern and central Finland.

Erkki Oksanen



Figure 2. Differentially defoliated Scots pines at Hietaperänkangas, Vanttauskoski, rural commune of Rovaniemi. Defoliation estimated using binoculars and defoliation classes arranged at 10% intervals.

Forest damage in Lapland at the end of the 1980s

Research looking into forest vitality and their state of health in Lapland was stepped up after the mid-1980s. In 1986, around 390 permanent forest-stand sample plots were established in Finnish Lapland to meet the requirements of the ILME project. These sample plots are mainly located in pine stands. Some of them are intended for what may be called extensive research while others are for intensive research. Measurements and observations made on the intensive level sample plots are repeated annually; on the extensive level plots this is done every five years. Assessments done on these sample plots include, for instance, assessment of relative defoliation.

Severest defoliation in Scots pine in northernmost Lapland

The annually repeated assessment of forest vitality during the years 1986–1989 revealed that Lapland's most severely defoliated pines were located in northernmost Lapland, around Inari (Fig. 2) (Jukola-Sulonen et al. 1993). The loss of needles by these trees increased by 10 percent points during the four year monitoring period. Needle loss increased with increasing tree age. In addition to being influenced by tree age and the northern location, needle loss by Scots pine in the Inari region of Finnish Lapland was also believed to be influenced by sulphur and heavy metal deposition originating from the Kola Peninsula.

Severe needle loss phenomenon in southern Lapland in the summer of 1987

Northern Finland's forests provided the setting for an unexpected phenomenon in the early weeks of the summer of 1987. In numerous stands located on peatland sites and sorted, nutrient-poor heathland mineral soil sites, conifers of varying ages



Eero Tikkanen

Figure 3. A young stand of Scots pine afflicted by marked needle loss at Hietaperänkangas, Vanttauskoski, rural commune of Rovaniemi, in July, 1987.

began to shed their needles prematurely. The shedding started from the oldest year classes of needles and advanced to the younger shoots. At first the afflicted needles turned yellow, and then, prior to being shed, brown. This damage was at its worst in Scots pine (Fig. 3).

Research into the causes of the premature needle shedding showed that the afflicted pines were suffering from disturbances in their nutrient and water status. Needle analyses showed that the afflicted trees translocated mobile nutrients from their old needles abnormally early to their juvenile, meristematic parts (Tikkanen & Raitio 1990a, 1990b, 1990/91, 1993). However, the afflicted trees' contents of nutrients that plants are unable to translocate were lower in the youngest shoots of the afflicted trees than in healthy trees and in trees in control areas.

The disturbances in the nutrient status of the trees were found to be caused by root injuries, since the results of soil analyses conducted in the study areas showed that the nutrient levels in the soil were equal to the average of equivalent sites. The primary cause of root damage was in the exceptional weather conditions of the years 1986 and 1987. The needle loss situation was at its worst in southern Lapland and Kainuu – regions where the above-average warm and rainy autumn of 1986 was followed by a steep fall in temperature in early December. Severe frosts froze up the almost snowless ground rapidly and to a great depth. Even in January 1987 the cover of snow was 20–30 cm below the average for that time of the year. The role of weather in the occurrence of the damage was further supported by the observation that roots are more susceptible to injury due to low temperatures than shoots and that the hardening of roots in preparation for winter begins later. Snow is important for roots in that it provides an insulating layer against low temperatures. This is especially so on nutrient-poor, lichen-dominated heathland forest sites, where the humus layer and the lichen layer are thin (the thinness of the latter being due to grazing by reindeer). In addition to being influenced by weather factors, the ability of trees to withstand external stresses may have been affected by airborne pollutants. Among other effects, these are known to cause discoloration of needles and their premature shedding.



Risto Jalkanen

Figure 4. A Scots pine infected by the Scleroderris canker (Gremmeniella abietina) at Lautakotaoja, Naruska, Salla, in June, 1988.

Scleroderris canker (*Gremmeniella abietina*) damage in Salla

In 1988, damaged stands of Scots pine were found in Salla, eastern Lapland, and along the Finno-Russian border. This damage was at its severest along the border zone and in the localities Rikkilehto and Lautakotaoja (both in Salla). The pines were discovered to be damaged by the Scleroderris canker (*Gremmeniella abietina)* (Fig. 4). The stands afflicted by this fungus pest were concentrated alongside watercourses and other low-lying places on the plateau bearing Scots pine (Kaitera & Jalkanen 1992).

Damage to the environment in the Kola Peninsula

Due to military policy reasons, the Kola Peninsula in northwestern Russia was an out-of-bounds region to foreigners for decades. The immense scale of the damage to the environment



Erkki Oksanen

Figure 5. The Severonikel nickel-copper smelter at Monchegorsk.

around the industrial centres of Nikel and Zapolyarnyy in the north-west and Monchegorsk in the central part of the Kola Peninsula was revealed to Finns as recently as in the late 1980s. The nickel and copper smelters established over fifty years ago in these industrial centres (Pechenganikel in Nikel and Zapolyarnyy and Severonikel in Monchegorsk) have caused marked loading of the environment and unparalleled damage to the forest ecosystems of the region (Fig. 5). Immense emissions of sulphur dioxide and heavy metals have completely destroyed the vegetation over vast areas and erosion has removed the soil overlying the bedrock (Fig. 6). Russian scientists estimate that industrial deserts, entirely or almost entirely void of vegetation, surrounding the smelter towns cover several hundreds of square kilometres (Kryuchkov 1991, 1993). The northern location of the afflicted areas has increased the susceptibility of the local ecosystems to the detrimental effects of airborne pollutants.

A report published in 1989 on the state of the environment in the then Soviet Union mentions the Kola Peninsula among the eight most seriously polluted eco-catastrophe areas (Report on the...1988). Some idea as to the amount of emissions of pollutants from the Kola Peninsula was obtained by Western scientists in connection with a joint-Nordic monitoring study conducted in the mid-1980s on heavy metals in mosses (Rühling et al. 1987). Similar observations were made in the late 1980s in the course of the aforementioned HAPRO project and in studies conducted by the Lapland Water and Environment District focusing on the acidification of watercourses in Finnish Lapland and in the Kola Peninsula (Kauppi et al. 1990, Kenttämies 1991, Kinnunen 1990, 1992).

The signs of forest damage observed in Finnish Lapland in the late 1980s, and the information made available on the emissions of pollutants from the Kola Peninsula and the damage to that region's environment, gave rise to suspect some link between them. The conception of an unpolluted Lapland and of its healthy, vigorous forests began to crumble. Forest owners in eastern Finnish Lapland fearing increment losses and other concerned citizens commenced to express demands for stepping up of forest damage studies and air quality measurements in Lapland. The news media were also increasingly vociferous as they joined in these demands.

Launching of the Lapland Forest Damage Project

In May, 1989, the Finnish Forest Research Institute (METLA) invited representatives of Finnish universities and research institutes to the METLA's Vantaa Research Centre to contribute ideas as to the stepping up of air-pollution-related forest damage research in Finnish Lapland. In addition to the METLA's own representatives, this meeting was attended by researchers from the Universities of Helsinki and Oulu, the Finnish Meteorological Institute, the Geological Survey of Finland, and the Lapland Water and Environment District. This meeting founded the five-year (1990–1994) Lapland Forest Damage Project and appointed the project a planning group and a project manager. Planning work for the project was commenced following the granting of a planning appropriation sum of 100 000 Finnish marks by the Ministry of Agriculture and Forestry.



Erkki Oksanen

Figure 6. Immense emissions of sulphur dioxide and heavy metals in Nikel have destroyed the vegetation from the hillsides and this has opened the way for erosion. The photo was taken 5 km north-east of Nikel.

Finnish research institutes and universities involved in wide-ranging co-operation

Following the founding meeting, the Universities of Kuopio and Turku (Åbo) and University of Lapland (the Arctic Centre) also joined in the project. All in all, the Lapland Forest Damage Project has been participated in by ca. 50 researchers from four universities and five research institutes. The METLA had personnel from its Helsinki and Vantaa Research Centres and the institute's research stations in Parkano, Suonenjoki, Muhos and Rovaniemi taking part in the project (Fig. 7). In addition to the contribution of researchers, the project has benefited from the involvement of field, laboratory and data processing personnel.

At the time the Lapland Forest Damage Project was launched, the HAPRO project had already come to its conclusion and the work of another research project SILMU (an acronym derived from the Finnish name of the research programme meaning The Finnish Research Programme on Climate Change) had not yet begun. This being the case, the Forest Damage Project had at its disposal some of the best Finnish resources in the field of environmental research.

Co-operation with Russian environmental researchers commences

Up until the late 1980s, the information available on the environmental research conducted in the Kola Peninsula was far from comprehensive. Among the earliest pieces of first-hand knowledge of this work was that provided by the Russian scientists who participated in an environmental seminar in Rovaniemi in 1988 (Kinnunen & Varmola 1990). It was not until the Lapland Forest Damage Project was launched that tangible research co-operation between Finnish and Russian scientists – forest researchers employed in the Kola Peninsula – began.

The first researcher visits from Finland to the problem areas in the Kola Peninsula took place in 1989. This was followed by the forming of contacts with the Kola Science Centre based in Apatity and research co-operation was commenced with the recently founded Institute of North Industrial Ecology Problems and researchers employed at this institute's Laboratory of Terrestial Ecosystems. Subsequently, the sphere of co-operation has been joined in by researchers from the Archangel Forest Research Institute's Monchegorsk Research Station and the Laplandia Nature Reserve (Fig. 7). These forms of co-operation have made it possible for Finnish researchers to work and collect material in Russian territory. Likewise, Russian researchers have made excursions into Finnish Lapland to collect material for their studies. In addition, they have worked at Finnish research institutes and participated in relevant environmental meetings and congresses held in Finland. Finns have also promoted the practice of joint publications with Russian researchers (Tikkanen & Varmola 1991, Tikkanen et al. 1992, Derome 1993).

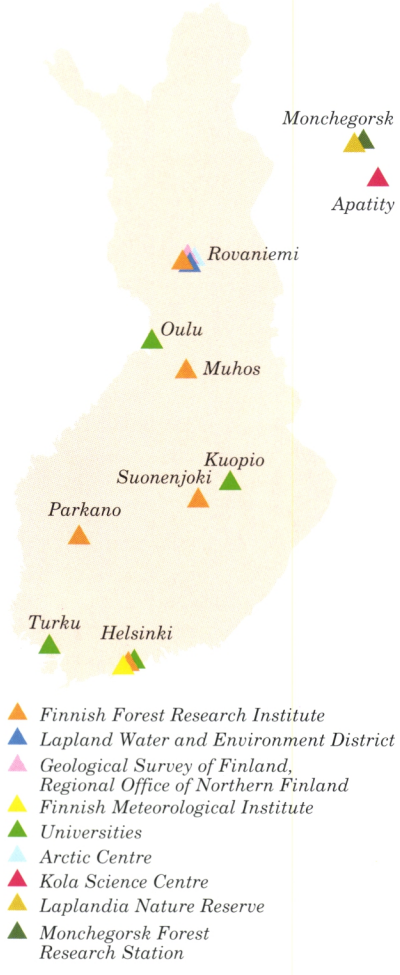


Figure 7. The Finnish universities and research institutes and the Kola Science Centre, the Monchegorsk Forest Research Station and the Laplandia Nature Reserve involved in the Lapland Forest Damage Project.

Sixteen subprojects

Initially, the Lapland Forest Damage Project comprised thirteen subprojects distributed among the universities and research institutes involved in the project in Finland. The overall co-ordination of the project was embodied in the co-ordinating subproject based at the MET-

LA's Rovaniemi Research Station. Using the project's results, the co-ordinating group has, for instance, compiled a database, which will continue to be updated at the Rovaniemi Research Station.

Assessment of the damaged areas in the Kola Peninsula began with the interpretation of satellite imagery. The impact of pollutant emissions on the region's forests commenced with studies looking into stress and damage symptoms in conifer needles, their chemical composition and frost-hardiness, the biochemistry and occurrence of the Scleroderris canker, the occurrence, functioning and structure of lichens on the stems and branches of trees, the litter on the forest floor, the chemical composition of bark and mosses, the soil and percolating water, soil microbiology, and the roots and growth of Scots pine. Three new subprojects were established during the years 1990–1992. These addressed the issues of air quality and deposition, and the influence that the lichen layer has on the soil and the frost-hardiness of Scots pine roots. All sixteen subprojects were appointed a responsible researcher (Fig. 8).

Challenging goals

The principal goal of the Lapland Forest Damage Project was to study the impact that pollutant emissions from the Kola Peninsula were believed to have on the forests of Finnish Lapland. Alongside this endeavour, there was the aim of producing basic scientific knowledge about Lapland's forest ecosystems and the changes taking place in



Figure 8. The Lapland Forest Damage Project's subprojects and their responsible researchers and units. METLA = The Finnish Forest Research Institute, FMI = The Finnish Meteorological Institute, Helsinki Univ. = The University of Helsinki, Turku Univ. = The University of Turku (Åbo), GSF = The Geological Survey of Finland, Oulu Univ. = The University of Oulu, AC = The Arctic Centre, Kuopio Univ. = The University of Kuopio. Photo: Erkki Oksanen, illustration: Aarre Jortikka.

them. Further goals included the pinpointing and delimiting of damaged areas in Russian territory; at the time when the project was launched, the information available on these damaged areas was of conflicting nature. The research data produced by the project is necessary when taking decisions on restrictions to be imposed on emissions. In the early 1990s, demands were expressed in favour of restricting emissions from the Kola Peninsula; some went as far as to demand their total elimination. The two basic solutions were either to refurbish the smelters or close them down.



Figure 9. The sample plots and sample plot lines used in the Lapland Forest Damage Project. The bigger black dots represent intensive sample plots and the red dots represent lichen sample plots. A = Angeli, M = Muonio, R-J = Raja-Jooseppi, N = Naruska.

Material and methods

The Lapland Forest Damage Project's planning group, which commenced its work in June 1989, decided to employ the gradient research method in the project. This method examines the impact that airborne pollutants have on the environment by taking into consideration the distance from the pollution source.

The gradient method is generally employed in studies where the study area is fairly small: i.e. when monitoring individual pollution sources or the surroundings of population centres. When dealing with large areas, problems are caused by natural, geographical variation (e.g. climate-related) which is independent of the pollution load. The use of the gradient method over the vast territory involved when examining Finnish and Russian Lapland was made possible by non-complex boreal ecosystems with their dearth of species and the fact that the pollution sources consisted of three smelter towns in the Kola Peninsula. A further aid when making observations of the situation was that there were no other equivalent pollution sources in latitudes above the Arctic Circle in Norway, Sweden, Finland or north-western Russia.

Sample plots established in forests on heathland soils

During the years 1989–1990, the METLA established sample plots in forests growing on dry and dryish heathland sites assumed to be sensitive to acidification. The forest stands thus sampled are pine-dominated with tree age varying between 80 and 200 years and an even or eastwards sloping topography. The sample plot interval along the south-west-, west-, and north-west-oriented gradient lines traversing Finnish Lapland is 4 km at the border, and then progressively increases to 8, 16 and 32 km as the distance from the pollution sources increases (Fig. 9). The establishing of sample plots in the Kola Peninsula in 1990 secured the continuation of the sampling lines from the border all the way to the pollution

sources. Intensive sample plots were also established in Svanvik, north-eastern Norway, in the same year.

A total of 133 sample plots were placed along the sampling lines. Of these, fourteen in Finnish Lapland, seven in the Kola Peninsula and two in Norway were subjected to more detailed study – i.e. they were what may be called intensive sample plots. In actual fact, the number of sample plots is several times greater because each sampling point consists of a cluster of 3–4 sample plots. Additionally, data collecting is concentrated to separate "sampling" sample plots as a means of reducing the human impact on the permanent sample plots (Fig. 10). The field measurements and collecting of material serving the needs of all subprojects were concentrated on the same sample plots – occasionally even the same trees.

In 1990 and 1991, a further sixteen "lichen sample plots" were established within the Lapland Forest Damage Project. The decision to do so was influenced by observations made in conjunction with the establishing of the intensive sample plots of the abundance of reindeer lichen communities in the Kola Peninsula. The lichen sample plots are located in western Finnish Lapland, in Angeli (Inari) and Muonio, and in eastern Finnish Lapland, in Inari's Raja-Jooseppi and Salla's Naruska (Fig. 9). These sample plots have enabled studies focusing on the influence of the lichen layer on the soil and the frost-hardiness of Scots pine roots.

Material ranging from satellite imagery to the subsoil

The range of material used in the Lapland Forest Damage Project comprised tree roots, mycorrhizae, fungi, lichens from the stems and branches of trees, ground lichens, mosses, needles, soil, percolating water, rain water and snow, and bark, litter and seeds of trees. Other research data were obtained in the form of increment borings, assessments of tree vitality, air and soil temperature measurements, and satellite imagery, the latter being used in locating and delimiting damaged areas. In addition to these, the project personnel made use of the data collected at the various air-quality monitoring stations in Lapland.

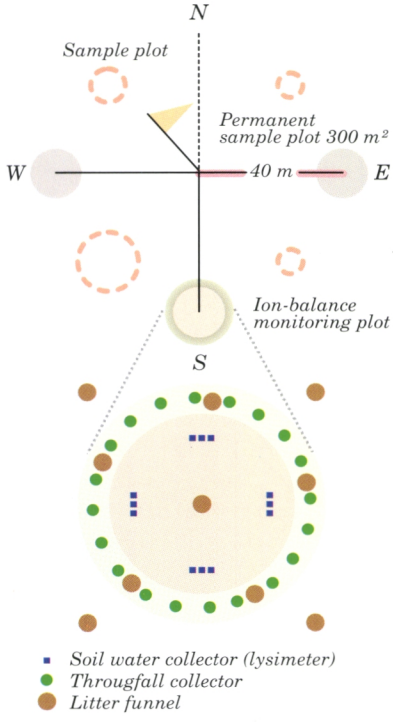


Figure 10. The structure of sample clusters in the Lapland Forest Damage Project. Each cluster is composed of 3–4 permanent plots. Of the 23 clusters, one is an intensive sample plot. There are 3–4 sampling plots per cluster.

Financing of the project

The funding of the project by Finland's Ministry of Agriculture and Forestry varied within the range of 3.0–3.7 million Finnish marks during the years 1990–1994. Over the five years of the project's activities, the Ministry granted a total of ca. 17.5 million Finnish marks. In addition to the funds from the Ministry, financing was directed to the project via the various participating research organisations. The METLA, for instance, invested nearly 10 million Finnish marks.

Final report in English

The Lapland Forest Damage Project's Interim Report was published in June 1992 (Kauhanen & Varmola 1992). The present publication is the 5-year-long project's Final Report in English, and it is based on the more comprehensive Final Report in Finnish published in March 1995 (Tikkanen 1995).

Following on from the chapter titled *Background to the research project and its implemen-*

tation, this publication contains an article of general interest on *The forests and forest research in Finnish Lapland*. The subsequent eight chapters then proceed to set out the centrally significant results obtained in the course of the project. The book ends with the chapter *Conclusions* reflecting upon the results achieved and the degree to which the Lapland Forest Damage Project's goals were fulfilled.

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The forests and forest research in Finnish Lapland

Author

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Figure 11. A view from the Pyhätunturi National Park, Kultakero slope, in Pelkosenniemi, over to vast expanses of forests and bogs of Peräpohjola, central Lapland. In the foreground the Tunturiaapa mire and in the background the Javarus fells. Photo: Erkki Oksanen.

The forests and forest research in Finnish Lapland

The forests in Fennoscandia (Norway, Sweden, Finland, the Kola Peninsula) extend further north than anywhere else in the world. Thanks to the nearness of the Gulf Stream, the conditions for forest growth are reasonable even in Finnish Lapland where one-third of Finland's land area, 16% of the country's timber resource and 10% of its annual increment are to be found.

Forest growth in Lapland is a slow process. Given the equivalent land area, forest growth there amounts to a mere fifth of what it is in southern Finland. Thanks to larger holdings and the marked presence of State forestry in the region, forestry in Lapland has been practised with efficiency.

Forests are of great importance to Lapland. Forestry industry accounts for 50% of the region's industrial production and 70% of its export earnings. Other important forest uses besides traditional forestry are conservation, reindeer husbandry, collecting of wild berries and mushrooms, hunting, and tourism.

The region's forests are also targets of intensive research. Wood production studies have, during the past few decades, been joined by studies emphasising other themes, especially forest health and multi-purpose forestry studies.

The boreal coniferous forest zone and the timber line

Development of Lapland's forest vegetation following the Ice Age

The present-day vegetation of Finland – and of Lapland – is the result of development since the end of the most recent glaciation (i.e. the Würm glacial stage) ca. 10 000 years ago. Birch, a pioneer tree species to this day, was quick to colonise the land revealed by the receding ice. During the boreal stage, ca. 6 800–5 500 B.C., the region's forests developed into mixed woods dominated by Scots pine but with an abundant admixture of broadleaved species. With climates warmer and more humid than the present one, the Atlantic climatic interval prevailed from ca. 5 500 B.C. to 2 000 B.C. In those times, the timber line, for instance, was located as much as 200 m higher up the fell sides than at present and paludification of forest land became more commonplace. Norway spruce arrived in Finnish Lapland from the east as recently as ca. 4 000 years ago and commenced to invade sites from pine.

The climate in Lapland has changed so little during the past 2 000 years that it has not decisively influenced the distribution of tree species. Short-term variation has, however, taken place. Cool summers, the crop-failure years of the 1860s, and especially the exceptionally warm years of the 1930s, when promising results were obtained concerning forest regeneration in the timber-line regions, are all examples of this variability.

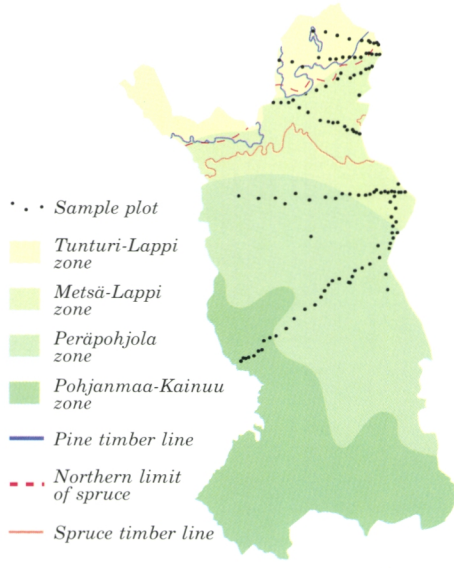


Figure 12. Northern Finland in terms of its vegetational zones and the distribution of conifers as shown in Suomen kartasto (1988) and the Lapland Forest Damage Project's sample plots.

Northern Finland in terms of vegetation zones

Finland falls within the coniferous forest zone encircling the Earth. Part of the coniferous zone lies within the boreal zone. Climatically, this zone corresponds to the cool zone (*Dfc* according to the Köppen-Geiger-Pohl scheme), where the mean temperature of one to three summer months exceeds +10 °C. North of the boreal zone is the Arctic-Alpine region, which belongs to the Earth's tundra vegetation zone. It comprises the tundra north of the timber line and the alpine areas above montane timber lines.

The southern part of Lapland belongs to the hemi-boreal zone, whose northern boundary follows the northern boundary of the Pohjanmaa–Kainuu vegetation region in Finland. Most of Lapland belongs to the northern boreal zone; within Finland, this zone may be subdivided into the vegetation regions of Peräpohjola and Metsä-Lappi (Fig. 12). North of the coniferous timber line lies the subalpine-subarctic birch forest zone. In Finnish Lapland, the two northernmost municipalities, Enontekiö and Utsjoki, cover most of this zone.

The region referred to as Pohjanmaa–Kainuu (or the Province of Oulu) is the transition zone between southern and northern Finland. Southern and northern flora and vegetation types meet here. Of the tree species, alder (*Alnus glutinosa*) is at its northern limit in the northern parts of this region. The southern limit to the abundant occurrence of dwarf birch (*Betula nana*) follows the region's southern boundary.

In the north, the Peräpohjola zone extends to the spruce timber line. Grove-like, lush forests are very rare there. The so-called thick-moss type (*Hylocomium-Myrtillus* type) is the characteristic forest type in Peräpohjola and Norway spruce (*Picea abies*) forms climax stands with an admixture of downy birch (*Betula pubescens*). Such forests have in many places been converted into plantations of Scots pine (*Pinus sylvestris*). There is an abundance of lichen-rich stands of pine.

The main tree species in the Metsä-Lappi (or Forest Lapland) zone is Scots pine. Birch occurs as an admixture among the pine; on more fertile sites, birch may be the main tree species.

Tunturi-Lappi (or Fell Lapland) is a transition zone between the boreal and arctic zones. This is a zone dominated by mountain (fell) birch (*Betula pubescens subsp. czerepanovii*); stands of Scots pine occur only in the larger river valleys. The flora in stands of mountain birch resembles that of the coniferous forest zone. The most extensive treeless fell-top areas are to be found in the Muotka fells (Inari), Pais fells (Utsjoki) and the North-west Arm (Enontekiö) (Fig. 13).

Several of the Lapland Forest Damage Project's sample plot lines cross over two forest vegetation zones. Sample plots along Line #1 fall within the Pohjanmaa–Kainuu and Peräpohjola zones. In the Russian territory the conditions on the sample plots show greater similarity with Metsä-Lappi than Peräpohjola. Due to variation in topography and local pollution sources (the towns of Kemi and Kemijärvi), Line #1 poses some problems. Line #2 is very representative of the east-west gradient. Sample plots on the Finnish side of the border along this line fall mainly within the Peräpohjola zone. Lines #3 and #4 pass through Metsä-Lappi while the northernmost Lines #5 and #6 mainly pass north of the pine timber line within the Tunturi-Lappi birch forest zone.

Pine forms the coniferous timber line in Finland

Contrary to the situation elsewhere in the Northern Hemisphere, it is Scots pine (not spruce or larch) which is the northern timber line species in Fennoscandia (inc. parts of the Kola Peninsula) (Fig. 12). Much

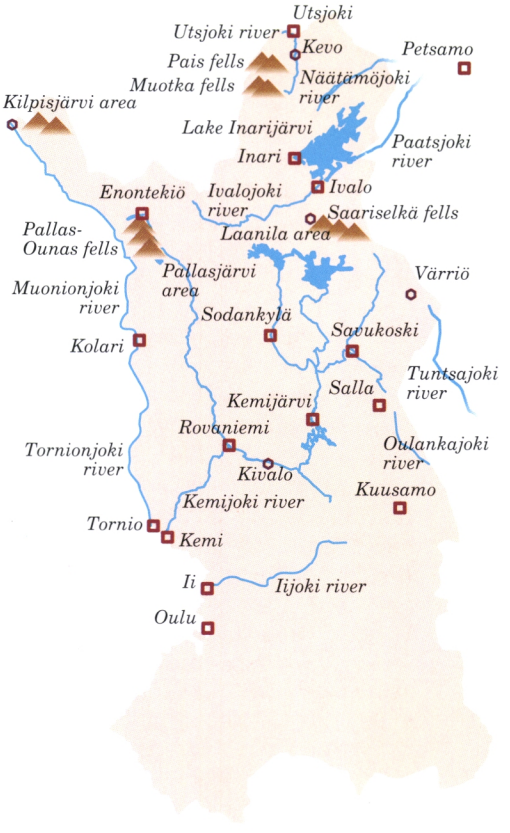


Figure 13. Treeless fell-top areas, main watercourses, the Finnish Forest Research Institute's research stations and areas and the Universities' research stations in Lapland.

favoured explanations for this phenomenon include distribution history of trees and climatic reasons. Edaphic factors have also been put forward.

The spruce timber line passes via Pallas-Ounas fells (in Enontekiö) to Ivalojoki river (Inari) and then on to the Saariselkä fells (Figs. 12, 13 and 14). Single spruces and clumps of spruces may, however, be encountered north of this line.

The pine timber line passes via the Enontekiö fell area to the Muotka fells and then along

the northern shore of Lake Inarijärvi to Näätämöjoki river (Figs. 12 and 13). North of this line, regular stands of pine are to be found only in the Utsjoki and Kevojoki river valleys, around Lake Pulmankijärvi, and along the shores of fjords on the Arctic Ocean.

Mountain birch occurs almost throughout Tunturi-Lappi. In the fells of the Inari region, as well as in some places to the south, but especially in the North-west Arm region of Finland, the climate becomes so extreme that mountain birch, too, has to give way to the treeless fell-top areas. Aspen (*Populus tremula*) will sometimes grow among the mountain birch. When it does, it often occurs as vegetatively arisen clones, extending into the Utsjoki river valley.

Climate the principal factor in determining the timber line

The present-day distribution of tree species is primarily the result of climatic factors. In addition to the temperature conditions during the growing season, critical temperatures significantly differing from the average temperature and wintertime winds also contribute to the formation of the timber line.

Topography determines the abruptness of the timber line. Conifers and birch appear to use the protection of depressions in creeping up the more gentle slopes. On steep slopes the timber line is very distinct.

The soil also has an influence on where the timber line occurs, especially in the case of spruce. In the northernmost Lapland, the soils are so deficient in nutrients that spruce cannot survive there. On the other hand, it may be that spruce has still not reached the peak of its distribution – after all, it arrived in what is now called Finland considerably later than pine. Biotic factors are also involved at the local level in the formation of the timber line. In 1965–1966, mountain birch over an area of ca. 500 000 ha in northern Norway, Sweden and Finland was damaged to varying degree by an epidemic of autumnal moths (*Oporinia autumnata*). At Kaunispää, in the Saariselkä fells of Finnish Lapland, pine sawflies (*Neodiprion sertifer*) kill pines on upland sites.

Forests under natural forces and the action of man

Wildfires moulded forest structure

Up until the turn of the century, wildfires played a role in the natural tree-species cycle within the boreal coniferous forest zone. Lit by lightning or man, these fires moulded the look of the forests. Spruce was forced to give way; birch, aspen and pine gained more room.

The area of state land annually burnt in the late 1800s has been estimated to have been 0.1–0.5% of the total area of forest land. Studies conducted in northern Sweden have arrived at an estimate of less than 100 years for the average interval at which wildfires have occurred in forests on dry heath-land soils. In northern Finland's thick-moss (*Hylocomium-Myrtillus*) type of spruce stands fires have occurred at considerably longer intervals, perhaps every 400–500 years. The most recent major forest fire in Lapland occurred in 1960 when ca. 20 000 ha of forest was burnt in the Tuntsa district of Salla, eastern Lapland. In Russian territory the affected area was even greater.



Erkki Oksanen

Figure 14. The northern timber line for Norway spruce (Picea abies) on top of Kuusipää, Saariselkä, Inari.

Early stages of reindeer husbandry and the spread of human settlement

The original Sámi (Lapp) settlement of Lapland was characterised by its sparseness. Reindeer husbandry, hunting and fishing were activities that did not require a great deal of wood. It was mainly firewood and construction timber for shelters and fencing that were consumed in those times. One sign of the impact that reindeer husbandry had on the forest scene was in the so-called *luppo* (beard lichen) swidden sites of the late 1880s: thousands of hectares of lichen-bearing spruce were felled in the winter to provide reindeer with emer-

gency fodder. It is also known that reindeer herders burnt remote pastures in order to make the reindeer stay closer to their camps. Out of envy and spite, too, some would burn the choicest lichen pastures.

The spread of the settlement of the country by Finns was accompanied by intensification of forest use. The swidden (also referred to as shifting cultivation or slash-and-burn) practice in agriculture, very common in southern Finland, was adopted as far north as Rovaniemi in the 1800s. Its common application, however, went no further than Kuusamo (Fig. 15). Farming in Lapland was mainly based on using the natural meadows along the banks of rivers and some clearing of arable land. Wasteful from the viewpoint of forestry, tar distilling was not practised in Lapland. In the Province of Oulu the situation was quite the opposite. There tar distilling was so popular in the 18th and 19th centuries that, in its peak times, the consumption of pine is estimated to have risen to ca. 3/4 of the present-day level in wood consumption. The northernmost tar distilling places were in the Iijoki river valley.

The human influence on the forests of Lapland remained moderate right up to the turn of the century. In southern and central Finland this was not so. The greatest impact was caused by forest fires, although these were usually confined to small areas due to the humid climate and the plentiful occurrence of peatland. To quote Claës W. Gylden, who was invited to make an assessment of Finland's forest resource, Lapland in the 1850s had "more than enough forests".

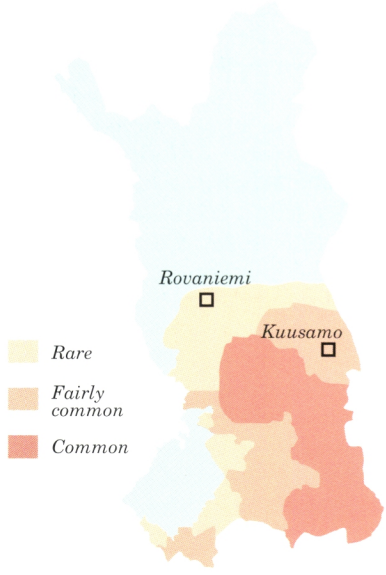


Figure 15. The extent of swidden (also referred to as shifting cultivation or slash-and-burn) agriculture in northern Finland in the 1860s.

Increasing use for wood

Finland's first steam-powered sawmill, the Kestilä sawmill, was granted its charter to begin operating at the mouth of the Iijoki river in 1857. This signalled the beginning of industrial consumption of wood in Lapland. In the course of the "Big Reallocation" of land in the mid-1800s, most of Lapland's forests went to the Crown. The Forest Service, the predecessor of today's Forest and Park Service, was created for the purpose of administering these lands. The mapping and inventorying of Lapland's forest resource began. The annual felling area system was adhered to in government forestry.

The principal felling method applied was diameter-limit felling, or culling for sawtimber. Although attempts were made by the Forest Service in government forestry as early as 1907 to shift over to forest management by stands, diameter-limit felling remained the sole method in public and private forestry right up to the early 1920s. Sawtimber-sized pine was the prime target. Forest regeneration was not practised and consequently the resulting stands became understocked. Exports of sawngoods were at their peak and wood was floated to the mills along the Tornionjoki and Kemijoki rivers. In the 1920s and 1930s, timber floating was also practised in northernmost Lapland, along the Paatsjoki river to the shores of the Arctic Ocean (Fig. 13).

Aimed especially at preventing a southward shift in the timber line and at imposing restrictions on the forestry practised in northernmost Lapland, the Protection Forest Act was passed in 1922. Some three million hectares of forest were set aside to act as a barrier against the tundra. The Private Forestry Act of 1928 provided means of steering and supervising private forestry. These Acts heralded the beginning of an era of systematic forestry in Lapland as well. Up to World War II, the forestry practised was mainly based on the felling of sawtimber-sized trees and confidence in natural forest regeneration.

Era of artificial regeneration in forestry begins

World War II and the subsequent territorial losses, reparations bills, reconstruction and resettlement caused a major change in the way that forestry



Erkki Oksanen

Figure 16. Ploughed pine regeneration site in Naruska, Salla, in August, 1994. The seedlings are infected by the Scleroderris canker fungus (Gremmeniella abietina).

was practised in Lapland as well. Immense logging operations were set up in remote wildernesses and unprecedented amounts of timber were felled. The reparations bills were paid for largely with timber from Lapland.

Expansion in forestry was not possible without some major changes being made regarding the logging methods applied. Diameter-limit felling was discarded in favour of active natural forest regeneration and especially artificial forest regeneration (i.e. renewal by sowing and planting). The primary policy adopted in exploiting the forest resource in Lapland was one of speedy and extensive regeneration of mature forests. This activity focused especially on the region's thick-moss (*Hylocomium-Myrtillus* type) stands of spruce as these were believed to be initially highly productive sites for forest growth. Clear felling and artificial regeneration to pine (initially by sowing following prescribed burning) became the standard solutions when dealing with these old stands of spruce. Site preparation by scarifying was also applied.

Planting of pine and ploughing as an aid in regeneration became popular practices in the 1960s (Fig. 16). This was also the time when mechanisation of forestry work got underway. Chainsaws replaced handsaws, forwarders replaced horses. The labourer with his hoe had to step aside when site preparation machinery, scarifiers and ploughs, drawn by bulldozers and forwarders, were brought to the forest. Drainage of peatlands for forestry became a mechanised operation with ploughs and mechanised diggers replacing manual work. The mechanisation of forestry work was "brought to conclusion" in the early 1990s: multifunction forestry machinery, typically harvesters, now carry out almost all of the timber harvesting in Lapland as well. The motor-manual alternative is employed when carrying out first-thinning, planting and sowing work in stony terrain inaccessible to mechanised systems.

The 1950s and 1960s were the golden era of timber floating (or river driving). In those years the annual roundwood volumes of timber transported by water were in excess of three million cubic metres. Road and rail transportation have subsequently taken over from floating. River driving on the Tornionjoki river ended in 1971 and in 1991 it ended on the Lapland main route of the Kemijoki river.

Forestry industry expands

Up to the 1920s, the consumption of wood by industry in Lapland was based solely on the demand coming from sawmills. Lapland's oldest large-scale forestry industry enterprise, Kemi Oy, was founded in 1893. The company originated from the stock of shares of a large, private company which had started as a sawmilling enterprise. In 1919, Kemi Oy built Lapland's first pulp mill in Kemi. The second such mill went into operation in 1927.

Lapland's biggest forestry industry enterprise, Veitsiluoto Oy, came into being when Parliament, in 1919, approved a bill for the founding of a new sawmill on the coast of the Gulf of Bothnia. The sawmill was built in Kemi in 1922, and the sulphite pulp mill went onstream in 1930. Thus was formed a firm base for the large-scale utilisation of wood in Lapland.

The next significant expansion of forestry industry was the founding of Kemijärvi Oy in 1965. Three years later this cellulose plant was merged with Veitsiluoto Oy. The Kemijärvi plant meant a considerable increase in the demand for timber from north-eastern Lapland.

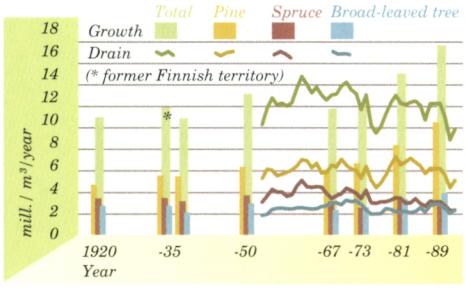
The stages in the development of forestry industry in Lapland are typical for Finland's integrated industry: the water-driven sawmills along the Kemijoki river were replaced by steam-driven mills and these in turn gave way to companies mainly active in the chemical forestry industry sector. Nowadays, forestry industry production emphasises printing and fine paper grades, cartonboard, cellulose, sawngoods and products serving the building industry.

Lapland's forest resource

The first inventories

Prior to the 1920s, estimates concerning Lapland's forest resource were mainly based on calculations made in conjunction with the mapping of government lands. It was not until the 1st national forest inventory (NFI-1), led by Academician Yrjö Ilvessalo and with the field work carried out during the years 1921–1924, that the first reliable information on Lapland's forests became available. The then area of Lapland, demarcated in accordance with the main watersheds, was found to contain a total wood volume of 343 mill. m^3 on forest land; this gave an average per hectare volume of 43 m^3. The proportion of pine-dominated forests of the area of productive forest land was at its greatest within the Arctic Ocean watershed area (76%). The proportion of pine-dominated stands in the areas adjacent to the Tornionjoki, Muonionjoki and the Kemijoki rivers was 53%, whereas within the eastern Tuntsajoki and Oulankajoki watersheds it was only 34% (Fig. 13). The proportion of peatlands was at its maximum within the Kemijoki watershed, namely 47.3% of the total land area. In the then Lapland, the proportion of peatlands averaged at 38%. A mere 24% of these were productive forest land.

Figure 17. Volume increment (o.b.) and total drain (o.b.) of the growing stock in northern Finland during the period 1916–1992. (Source: NFI)



In 1936–1938, just before World War II, Yrjö Ilvessalo supervised the 2nd national forest inventory (NFI-2) over the then territory of Finland. The results of the inventory revealed that the country's forest resource had decreased by ca. 25 mill. m^3. In other words, wood harvesting had clearly exceeded growth.

The results of the NFI-3 (conducted in 1952–1953) showed, to everyone's surprise, that Lapland's forest resource had now increased. The total volume recorded was 310 mill. m^3. This was most probably due to the exceptionally warm climatic period and reduced harvesting during the war years. This contributed to a policy of significantly increased felling of timber in Lapland.

The fourth national forest inventory, the NFI-4 (1962–1963), led by Yrjö Ilvessalo, was the last one based on the method of systematic line survey. The effect of increased felling showed up clearly in the results. The volume of the growing stock had reduced by 40 mill. m^3 in the space of fifteen years. The fall was most marked in the case of pine volumes. Forest growth had also decreased despite the creation of extensive regeneration areas.

The current forest structure

Since the NFI-4, Lapland's forests have been inventoried once every 10 years on average. Professor Kullervo Kuusela supervised the NFI-5 (1969–1970), based on the block method. The NFI-6 (1970, 1974–1976) and the NFI-7 (1978, 1982–1984) of Lapland's forests, developed by Professor Simo Poso, forest engineer Matti Kujala and doctor Eero Mattila, were carried out using combinations of two-phased interpretation of aerial photographs and field measurements. The results obtained from the inventories demonstrated the impact that extensive felling had had on the growing stock. The increase in the proportion of growth contributed by juvenile stands and drained peatlands has increased the total annual forest growth in Lapland from 6.1 mill. m^3 (NFI-5) to 7.55 mill. m^3 (NFI-7). The increase in forest growth has also led to an increase in the total volume of the forest resource since the days of the NFI-5. However, the total volume is still less than it was in the 1950s.

The annual growth of pine, spruce and broadleaved species in northern Finland (i.e. the Province of Lapland and most of the Province of Oulu), a region for which inventory results have been output since the NFI-1, varied between 11 and 13 mill. m^3 in the results provided by the first five inventories (Fig. 17). In the 1980s the increase in growth was vigorous. With felling focusing on mature forests, the annual drain exceeded annual growth up to the 1970s. Felling was at its height in the 1960s. The slump of the mid-

1970s, as well as the 1990s' recession, clearly stand out in the drain figures. For Lapland, too, the 1990s has been a period of surplus growth.

Scots pine is the leading tree species in Lapland. It accounts for 60% of the region's total growing stock volume. In the three northernmost municipalities of Utsjoki, Enontekiö and Inari, pine accounts for 93% of the area of forestland and scrubland combined. Birch dominates the so-called wasteland category of forestry land in the fell areas; these are of little value from the viewpoint of forestry. Elsewhere in Lapland, the proportion of pine falls slightly as one moves eastward. On combining forestland and scrubland in the jurisdiction of the Lapland Forestry Board, pine is the dominant species on 70% of the area. The corresponding figure for the Koillis-Suomi Forestry Board (northeastern Finland) is 65%.

According to the results of the NFI-7, 40.8% of northern Finland's total land area consists of peatlands; i.e. about as much as at the time of the NFI-1 for the corresponding land area. In Pohjanmaa–Kainuu (i.e. the Province of Oulu) roughly half of the peatland area has been drained but in Lapland only 23%. Due to drainage for forestry, the proportion of productive forest land in the total peatland area in northern Finland has risen to 37%. In Lapland this figure is 25%.

The majority of Finland's conservation areas are located in Lapland (Fig. 18). The foremost areas set aside to protect specific forest ecosystems are judicial reserves: strict nature reserves, national parks and wilderness areas. In addition to these, the Forest and Park Service has set aside old-growth forests and nature-management forests through internal decisions. The Service has also placed some upland forests outside the sphere of normal wood production. Forestland and scrubland within the sphere of normal forestry amount to ca. 5.2 mill. ha of Lapland's total of 9.6 mill. ha; the rest comprises scrubland in terms of wood production capacity and areas set aside for conservation. It has been estimated that the growing stock set aside for conservation reasons has reduced the maximum sustainable allowable cut in Lapland by more than 1 mill. m^3 per year.

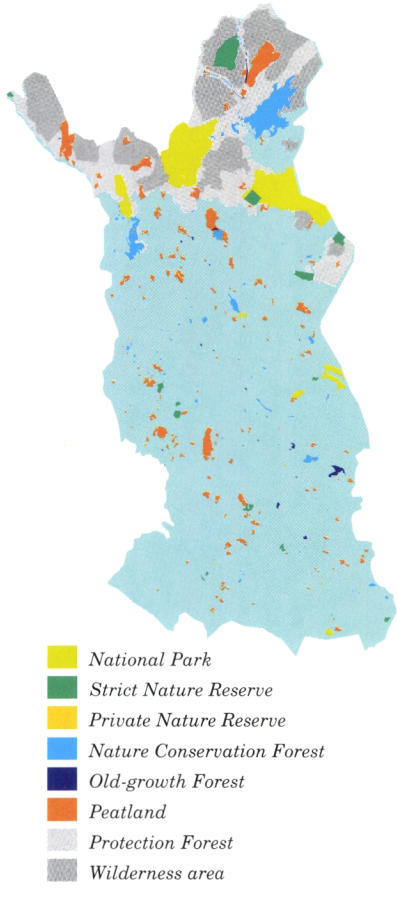


Figure 18. Conservation areas and other protected areas in northern Finland.

The sample plots serving the Lapland Forest Damage Project were established on pine-dominated dryish and dry heathland forest sites. The proportion of these forest types is at its maximum in the northern part of the Lapland Forestry Board's jurisdiction, where they amount to 72% of the area of forestland on mineral soil sites. Elsewhere within the said jurisdiction their proportion is 62%. The corresponding figure for the Koillis-Suomi Forestry Board jurisdiction (eastern northern Finland) is 49%. The majority of these heathland soils carry pine-dominated forests and thus the sample plots represent the most typical forest cover in Lapland in terms of tree-species composition (Fig. 19).

Research – the cornerstone of forest use

Pioneers of forest research in northern Finland

The launching of forest research in Lapland is connected to the Forest Service's (the predecessor of the present-day Forest and Park Service) interest in the forests placed in its care – in their structure, how to manage and regenerate them. August Renvall, the Service's District Forester at Utsjoki, was the author of the first scientific work, his doctoral dissertation, dealing with forest research in Lapland. Published in 1912, his

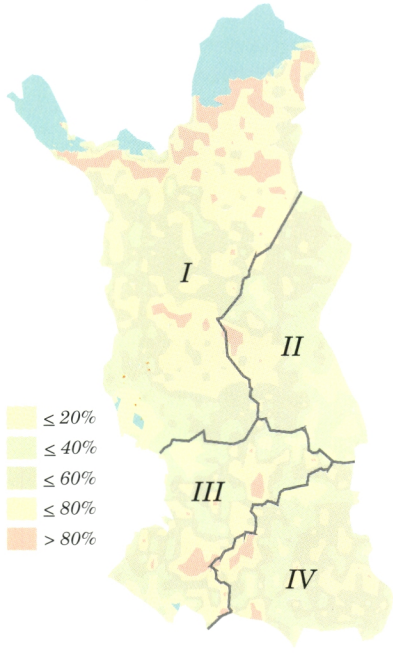


Figure 19. Occurrence of pine-dominated dryish and dry heathland forest soils in northern Finland and the jurisdictions of the forestry boards in northern Finland. I = Forestry Board of Lapland, II = Forestry Board of Koillis-Suomi, III = Forestry Board of Pohjois-Pohjanmaa, IV = Forestry Board of Kainuu. (Source: NFI)

thesis addressed the subject of flowering, cone and seed production of Scots pine "on the polar timber line", a subject which continues to have relevance. Renvall also carried out forest regeneration trials north of the timber line.

Besides Renvall, Professor Olli Heikinheimo, soon to be appointed head of the Experimental Forest Institute (today's METLA for short), deserves a special mention. He published significant studies in the 1910s and 1920s on the forest use in Lapland: on the silviculture to be applied in the northern Finland's spruce forests, the snow-damage areas of Finland and the forests of these areas, and on Finland's timber-line forests and their future use.

Yrjö Ilvessalo, the innovator and leader of national forest inventories in Finland, studied the structure of Lapland's forests in the 1930s in his work titled "*Growth of natural-normal stands in North-Suomi (Finland)*". This work continues to hold its position as a basic study on the development of untouched forests in Lapland.

An extensive network of experimental areas (today's research areas) was set up and placed under the jurisdiction of the then Experimental Forest Institute (predecessor of today's METLA): Kivalo in 1924, Laanila in 1925, Petsamo in 1927, Kilpisjärvi in 1940 and Pallasjärvi in 1945 (Fig. 13). The Kivalo area stands out among these as a place which provided forestry in Lapland with particularly useful information on forest regeneration, the cultivation of exotic tree species, forest fertilisation, and drainage.

From selection felling to forest regeneration studies

In 1950 Professor Risto Sarvas published his study on the regeneration of selection-felling forests in private, non-industrial ownership in Peräpohjola. The results presented in the study had a major impact on the development of methods employed in connection with natural regeneration in Lapland as well. Selection felling was discarded in favour of the seed-tree and shelterwood systems.

The results obtained from the regeneration experiments established by Heikinheimo in the 1920s and 1930s were particularly useful in indicating the good growth achieved with pine on regeneration sites of the spruce-dominated, thick-moss (*Hylocomium-Myrtillus*) type. Professor Gustaf Sirén's doctoral dissertation, published in 1955, is a thorough treatment of the development and ecology of northern Finland's spruce forests on sites classified to be of the thick-moss (*Hylocomium-Myrtillus*) type. Sirén's view was that these forests were deteriorated secondary stands of the *Myrtillus* type, and that artificial regeneration would be the way to make the sites productive once again. Sirén, too, was in favour of prescribed burning and regeneration to pine through sowing.

The 1950s were a period of rapid increase in the adoption of artificial regeneration. A further-training seminar arranged by Finland's Society of Professional Foresters in 1954 provided the setting for the formulation of guidelines for the development of forestry in Lapland. With the participation of respected, leading figures in Finnish forestry, the book published following the seminar, "*Lapin metsien mahdollisuudet*" ("The potential of Lapland's forests"), relying largely on research results, presented a picture of great promise for forestry in the region. The resolution proposed the expansion of forestry industry, increasing the efficiency and effectiveness of forest management, improvement of timber transportation, launching of forestry training courses aimed at the rural population, and the establishing of a specific "Department of Northern Finland"

within the METLA. All these proposals have been realised.

Research stations run by universities

In addition to the contributions of the METLA's research personnel, their colleagues in the service of universities have carried out numerous studies in the fields of biology, including studies connected to the forests of Lapland. The first university to set up a research station in Lapland was the University of Turku, whose Kevo Subarctic Research Station was established at Utsjoki in 1956 (Fig. 13). Initially, the research work done at the station focused on the ecology of birch, especially of mountain (fell) birch, and on matters connected to the timber line. An arboretum comprising all the tree species that occur on the boreal timber line was established there in the 1970s. In recent years, research at Kevo has been directed at experimentally clarifying the impact of the Kola Peninsula emissions. The trials established for this purpose have included mountain birch and pine, and the insects that feed on them.

The University of Helsinki's Kilpisjärvi Biological Station was founded in 1964 (Fig. 13). It is located in Finland's severest climatic conditions. The station's staff conduct eco-physiological research and environmental research. Monitoring series going back to the 1940s have earned the station fame. Forestry-related studies carried out at the station include mountain birch, the timber line, and climate change and its impact on tundra vegetation.

The University of Helsinki's Värriö Research Station was founded in 1967 (Fig. 13). The zoological studies of the early years have been supplemented with studies involving the forestry sciences. Studies focusing on the gas-exchange reactions of Scots pine in extreme boreal conditions have in recent years expanded into the sphere of pollution studies in the Kola Peninsula: sensitive analysis methods are being employed to determine the impact of different concentrations of pollutants on the eco-physiology of Scots pine.

The Finnish Forest Research Institute's research stations

The Finnish Forest Research Institute (METLA) has two research stations in Lapland, in Kolari and Rovaniemi (Fig. 13). The METLA's Kolari Research Station was founded in 1964. The research conducted there is currently mainly connected to forest tree breeding and peatland forestry. Timber line issues are also currently addressed at the Kolari Research Station.

The origins of the METLA's Rovaniemi Research Station are interlinked with the problems encountered in forest regeneration. Extensive failures in artificial forest regeneration took place in Lapland in the late 1960s. The primary cause behind the failures was found to be the Scleroderris canker (*Gremmeniella abietina*) (Fig. 16).

Research work at Rovaniemi began in the spring of 1970 and focused at first on clarifications aimed at ensuring the success of forest regeneration, especially of artificial regeneration. Already in the 1970s, the station's research activities came to include multi-purpose forestry, wood production, forest inventories, business economics of forestry, and forest soil science.

In the late 1980s, forest health studies were commenced at Rovaniemi. This followed the reform in research strategy implemented within the METLA, but most of all it was due to incidents of forest damage observed in Lapland's forests and the involvement of the station in clarifying them. Basic knowledge on the reaction of Lapland's forests to changes brought about by human activity was lacking. Steps to eliminate these gaps in knowledge began to be taken in the late 1980s. In recent years, more than a quarter of the Rovaniemi Research Station's resources have been directed into research delving into the impacts of airborne impurities and other human-related effects.

Environmental research of increasing significance

Finnish Lapland offers a prime natural laboratory for the needs of environmental research: the conditions for growth can be extreme harsh and human activity influences the region's forests right up to the timber line. Areas of extreme forest growth are readily accessible and significant point sources of pollution are close at hand. Finnish Lapland and the environmental research conducted there are also of great interest to researchers abroad.

The character of environmental research has undergone changes. The problems studied are so diverse that wide-ranging

co-operation is required among research institutes – both at home and abroad. The increasing efficiency with which the natural resources of the Barents region will be exploited in the future means that new challenges are in store for this branch of scientific research.

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Air quality and deposition

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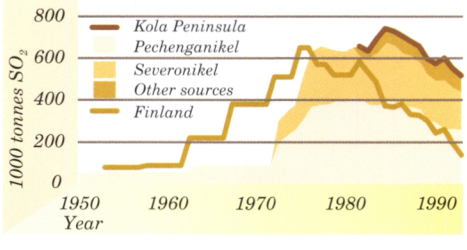
Figure 20. Chimneys and flue gases of the Severonikel metal smelter in Monchegorsk. Photo: Erkki Oksanen.

Air quality and deposition

Since the early 1970s, the Finnish Meteorological Institute has made measurements of wet deposition and average atmospheric sulphur dioxide concentrations at the institute's stations in Sodankylä and Kevo (Utsjoki). Also the National Board of Waters and the Environment has long series of deposition observations from a few stations in northern Finland. However, the monitoring of average levels did not sufficiently clarify the special characteristics of air quality in Lapland. Consequently, actual concern over the quality of the air in Lapland began to be expressed as recently as the late 1980s, when the first reliable information concerning the immense emissions from the Kola Peninsula was obtained (Figs. 21 and 22).

Starting in the autumn of 1989, measurements of the concentrations of atmospheric sulphur dioxide have been made as 24-hour averages at Värriö (Salla) and Oulanka (Kuusamo). Ozone and nitrogen dioxide measurements by continuously registering devices have also been included in the measurements carried out at Oulanka. Continuous measurement of sulphur dioxide concentrations has been carried out at Jäniskoski, east of Lake Inarijärvi, since the spring of 1990.

Figure 21. Development of sulphur dioxide emissions from the Kola Peninsula during the period 1980–1992 and the corresponding data for Finland since the year 1955. The emissions from Pechenganikel are estimates starting in 1946 and from Severonikel starting in 1970. (Source: e.g. Blatov, I. et al. Ilmansuojeluuutiset 3/1992)





Erkki Oksanen

Figure 22. The Pechenganikel nickel-copper smelter at Nikel.

Measurement of heavy metals in wet deposition was commenced at Utsjoki and Kuusamo in 1990. In 1991, these were joined by the continuous measurement of sulphur dioxide and ozone concentrations at Sammaltunturi, in western Lapland; in 1992 the same measurements began to be made at Raja-Jooseppi, east of Inari. The Sammaltunturi station is in the process of being upgraded into a more versatile measurement station in compliance with the requirements of the World Meteorological Organisation. The impact on Lapland of the emissions from the Kola Peninsula is at its worst in the eastern part of the Inari region. This is the region for which the Sevettijärvi air-quality measurement station was established in the autumn of 1991 to meet the requirements of the Lapland Forest Damage Project. The costs of building the station were shared by the Forest and Park Service, the Meteorological Institute, the METLA, and the municipality of Inari. The measurements carried out at the station are more specialized than normally as the aim is to obtain a more comprehensive picture of the properties of the pollution load affecting the region.



Figure 23. The most significant localities in terms of emissions of sulphur dioxide in Finnish Lapland and the Kola Peninsula in 1990 and those air-quality measurement stations whose data were used in the Lapland Forest Damage Project. The emission units used are 1 000 tonnes of sulphur dioxide.

Following the above development work, Lapland now possesses Finland's densest and best-equipped measurement network for monitoring air quality (Fig. 23). The information

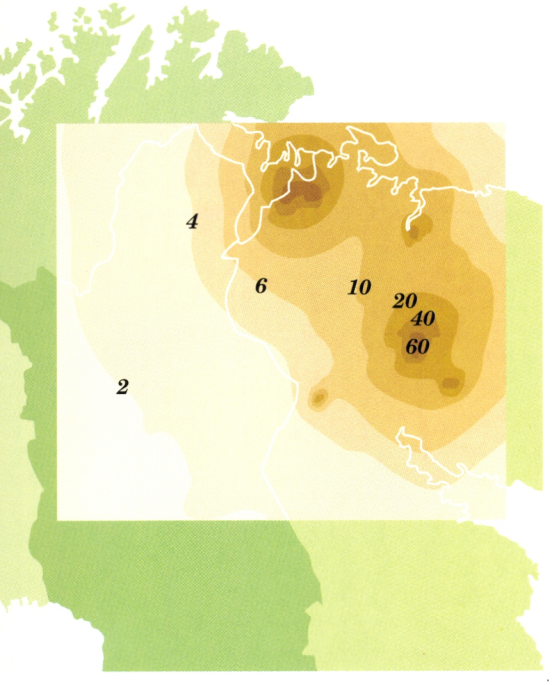


Figure 24. The regional distribution of the average of estimated atmospheric sulphur dioxide concentrations (µg/m³) during the period July 1990–June 1991 in the Kola Peninsula and Finnish Lapland.

obtained concerning the quality of the air in this northern region is supplemented by measurements done by the Norwegians over their territory. The material used in this project comprises data obtained from the aforementioned air-quality measurement stations, the Lapland Forest Damage Project's deposition measurements, and numerous separate studies connected to the air quality in Lapland.

Main results

The most typical feature of the pollution climate in Lapland is its occasional, high sulphur dioxide concentrations. In the Inari region of Lapland, which lies closest to the emission sources in the Kola Peninsula, concentrations have been recorded to rise to hundreds of micrograms per cubic metre of air when the winds blow from the east. The resultant peaks usually endure for a few hours. Less than one percent of the hourly sulphur dioxide readings exceed 100 µg/m³. Concentration peaks also occur in western Lapland, but diluted to ca. 1/10th of the values recorded in eastern Lapland.

When the winds blow in from the north and the west, the air they bring from the Arctic and the North Atlantic is very clean. Southerly winds bring in pollutants from southern Finland and from continental Europe. Despite the occasional peak, the average of estimated atmospheric sulphur dioxide concentrations almost throughout Lapland remain within the range of 1–5 µg/m³, which is clearly below the level believed to be critical for forest ecosystems (Fig. 24). The year-round, reoccurring short-term exposure, which is characteristic of the

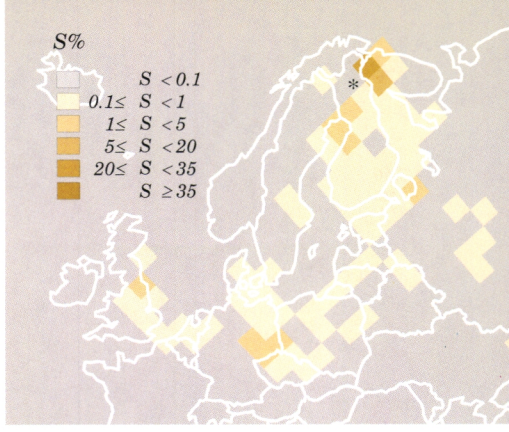


Figure 25. The origin of central Lapland's sulphur deposition presented as relative proportions and 5-year averages. (Source: EMEP MSDC-W)

situation in Lapland, does not, however, stand out with sufficient clarity in the critical level defined in terms of the annual mean.

The acidity of the deposition in Lapland is regulated by the sulphuric acid formed from sulphur dioxide. Oxides of nitrogen, on the other hand, are almost without any acidifying significance. The deposition in Lapland has but little neutralising components. Consequently, the annual acid deposition does come to roughly half of that recorded in southern Finland. The

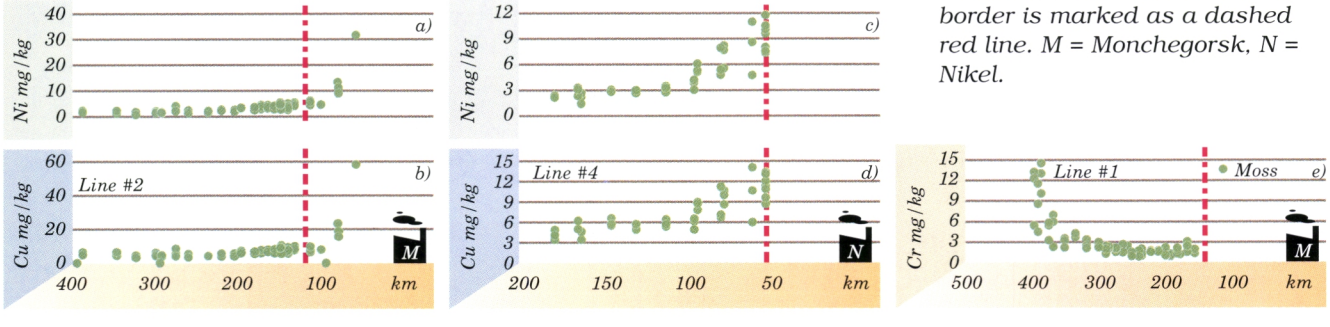


Figure 26a–e. Nickel and copper concentrations in mosses (Pleurozium schreberi, Hylocomium splendens) along sample plot Lines #2 (a, b) and #4 (c, d) and chrome concentrations along Line #1 (e). The Finno-Russian border is marked as a dashed red line. M = Monchegorsk, N = Nikel.

annual acid load imposed on the soil in Lapland can rise to levels as high as 15–20 meqv/m^2; i.e. close to the critical level.

Atmospheric sulphur dioxide accumulates on vegetation in the form of dry deposition. The amount of dry deposition is proportional to the atmospheric concentrations of sulphur dioxide. Since high sulphur dioxide concentrations have been recorded in the Inari region of Lapland also during the growing season, the accumulation of sulphur dioxide can be expected to have a major role in the overall load imposed on the region. Calculations indicate that as much as over 60% of the total deposition of sulphur in the Inari region is accounted for by dry deposition. However, dry deposition is difficult to determine. For the present, it has not been possible to confirm whether it plays an important role in Lapland.

The sulphur dioxide emissions from the Kola Peninsula have a distinct impact over a radius of a couple of hundred kilometres from the emission sources. Around half of the sulphur deposition in central Lapland originates from the Kola Peninsula (Fig. 25).

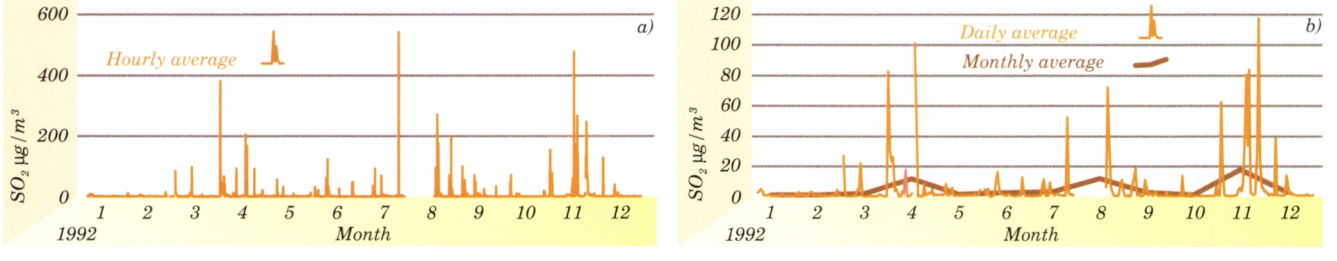
Depositions of nickel and copper have risen dramatically in the vicinity of the Kola Peninsula smelters. The amounts quickly decrease with increasing distance away from the smelters; on the Finnish side of the border, the values recorded are close to the background values. On the eastern side of Lake Inarijärvi, the concentrations of nickel and copper in the bark of pine trees are three-to-five times greater than in western Lapland. Slight increases in copper and nickel concentrations have been detected in the bark of pine trees and in mosses at distances of 100–200 kilometres from the Kola emission sources. The deposition of chrome originating from Tornio, at the tip of the Gulf of Bothnia on the Finno-Swedish border, shows up in mosses at distances of over 100 kilometres from the source (Fig. 26a–e).

Ozone concentrations in the spring are high throughout Finland. This is the time of the year when the pollutants that have accumulated in the atmosphere over the winter form ozone under the influence of the spring sunshine. During the summer the ozone concentrations are especially high in the southern and central parts of the country, the regions most heavily afflicted by long range transportation of pollutants and domestic emissions. When the atmospheric concentrations of ozone over Lapland are compared to the guideline values applied internationally, it becomes apparent that damage to the vegetation can result, especially in the region's southern parts.

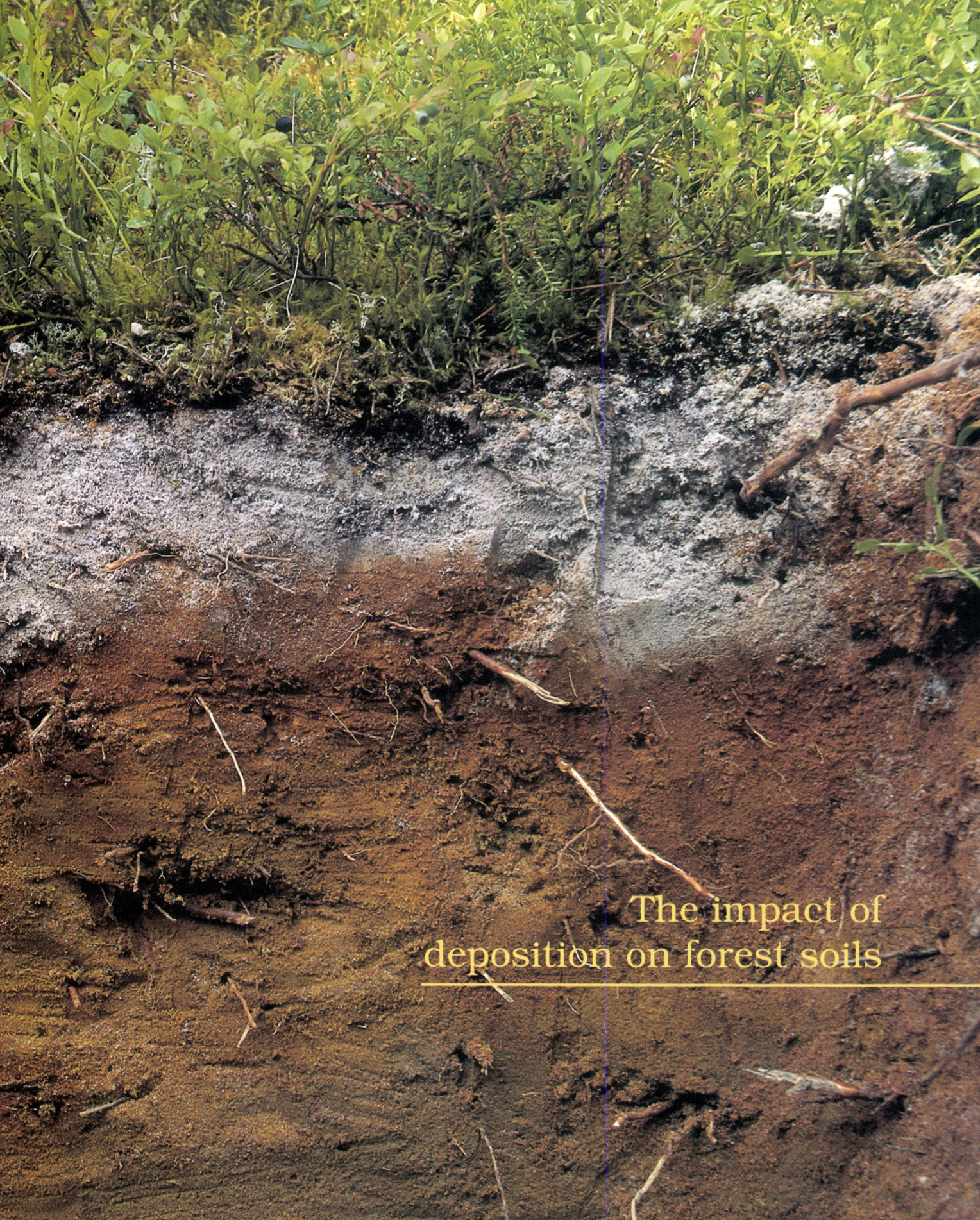
On average, the air over Sevettijärvi is very clean: 50% of the sulphur dioxide concentration hourly averages in 1992 and 1993 were below 1 µg/m^3. Once or twice a month there were pollution episodes with the pollution load originating from the Kola Peninsula smelters. These lasted a few hours, during which time the sulphur dioxide concentrations exceeded 100 µg/m^3 (Fig. 27a and b). Often these episodes were accompanied by impaired visibility and a rise in the relative humidity of the air. Easterly winds were responsible for 60–70% of the exposure to sulphur dioxide.

The particles contained in the air over Lapland proved to be acidic when examined in the course of this project. This is due to the fact that the sulphuric acid formed from the sulphur dioxide does not become diluted in the atmosphere because of lack of ammonium. Heavy-metal analyses made of the particle samples revealed that especially nickel, copper, cadmium, lead, zinc and vanadium are carried over to Sevettijärvi from the Kola Peninsula smelters. Zinc and lead are also brought to Sevettijärvi by southerly winds during pollution episodes.

Figure 27a, b. The concentrations of atmospheric sulphur dioxide at Sevettijärvi, Inari, in 1992.







The impact of deposition on forest soils

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Figure 28. Podzolised soil on the intensive sample plot in Kemijärvi. Photo: Erkki Oksanen.

The impact of deposition on forest soils

Forest soils are the outcome of the interaction between soil, climate, vegetation, fauna and human activity. The top layer is composed of mineral soil and dead and living organic matter. The texture and chemical composition of the soil have a strong effect on the species composition and biomass production of the vegetation cover. Since they regulate the supply of nutrients and water essential for plant life. The plants in turn influence the biological and chemical properties of the soil.

A state of dynamic balance prevails between the vegetation and the underlying soil. The high temporal and spatial variation in soil properties cause numerous problems for the soil scientist, and it is very difficult to distinguish between natural changes in the soil and those caused by human activity.

Figure 29. Collecting wet deposition samples on the intensive sample plot near Monchegorsk.



Erkki Oksanen

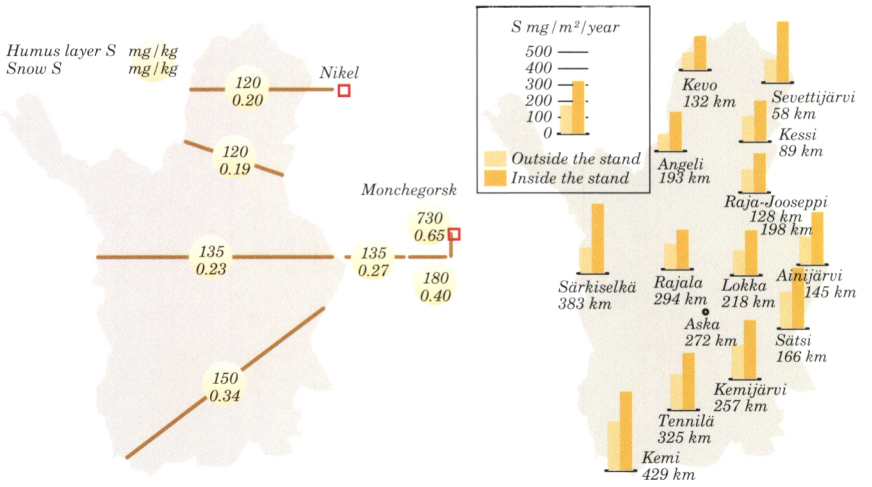


Figure 30. Mean extractable sulphur concentration in the humus layer in 1990 and the mean total sulphur concentration in the snow in March 1991 and 1993 along Lines #1, #2, #3 and #5.

Figure 31. Annual deposition of total sulphur as free wet deposition and stand throughfall on the intensive sample plots in Finnish Lapland between June 1990 and May 1993. The distances to the sample plots are from Monchegorsk (for Ainijärvi, Sätsi, Raja-Jooseppi, Lokka, Kemijärvi, Aska, Rajala, Tennilä, Särkiselkä, Kemi) and from Nikel (for Sevettijärvi, Kessi, Raja-Jooseppi, Kevo, Angeli).

The chemical properties of forest soils are reflected in their ability to counteract the influence of acidic deposition. The main determing factor is the total amount of base cations in the top layer of the soil. In some parts of Lapland the capacity of the soil to resist acidification is fairly low.

As well as geological aspects, climatic factors also have a strong effect on the properties of the topsoil. The humus layer in northern Finland is on the average more acidic than that in southern Finland, but the 5–20 cm thick mineral soil layer less acidic. This is primarily due to the accumulation of acidic, relatively undecomposed material in the humus layer as a result of the short growing season and cold, moist conditions in the north. The occurrence of relatively unweathered, underlying mineral soil in the north could also be attributed to the lower annual precipitation and longer duration of frozen ground in the area.

The composition of the vegetation is another factor influencing the soil's ability to resist the acidifying impact of acidic deposition. Lichen communities are characteristic of nutrient-poor heathland soils bearing stands of Scots pine. The lichens and various Ericaceous plants cause some degree of acidification of the soil through the exudation of acidic substances. Thus acidification is also a natural phenomenon previously disrupted by periodic forest fires.

Since the soils underlying pine stands are naturally acid, their microbial flora have adapt-

ed to life under nutrient-poor conditions. Slight acidification is thus not a major obstacle for soil microbes in nutrient-poor, heathland pine stands until the pH of rain water approaches a value of about 3.5. The ability of pine root systems to resist the impact of acid deposition is not known. However, since the roots of these plants are also adapted to acid conditions, it can be assumed that deposition will not damage them in the short term. To date, no cases of damage caused by heavy metals in nutrient-poor conditions have been reported.

The purpose of this research work was to report on the quality and quantity of the deposition reaching the forest soil and to assess its impacts on the soil in Finnish Lapland and in the Kola Peninsula (Fig. 29). Since the nutrient status of pine depends on the condition of its root system and soil microbes, these were included in the impact assessment. The main results obtained concern the period 1989–1993 and sample Lines #1–6 of the Lapland Forest Damage Project.

Figure 32. Base saturation of the humus layer along Line #1 in 1990.

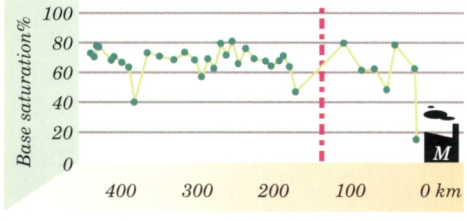
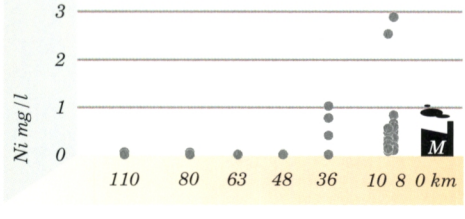


Figure 33. The concentrations of nickel in the percolation water (5 cm from the soil surface) on the intensive sample plots in the Kola Peninsula between June and September, 1993. 8 km = Monchegorsk #1, 10 km = Monchegorsk #2, 36 km = Imandra, 48 km = Pirenga, 63 km = Upoloksha, 80 km = Yena, 110 km = Kovdor.



Main results

The Monchegorsk emissions have not influenced the chemical or biological status of the most sensitive forest soils in Lapland as a whole. This is mainly due to the relatively low deposition of acidifying sulphur compounds and heavy metals on the Finnish side of the border. Owing to the topography and prevailing wind directions, the emissions are mainly carried to the north and south of the smelters. The sulphur concentrations of wet deposition, snow and humus in Finnish Lapland indicate, however, a clearly decreasing gradient running from south to north that is attribute to emissions from southern Finland and Central Europe (Fig. 30).

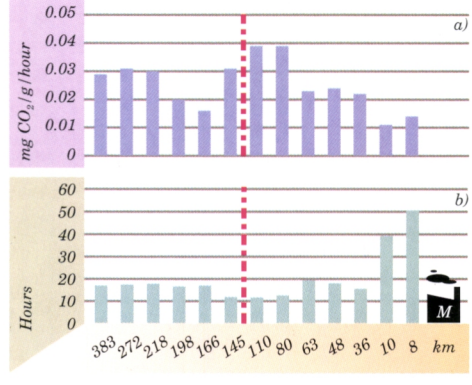
Some changes in soil properties have taken place in the eastern part of the Inari region close to the Nikel smelter complex. These changes are probably the result of heavy metal deposition, as well as to some extent acidifying deposition. Sulphur uptake in the pine forests of this region has clearly increased (Fig. 31).

The chemical and biological changes in the soil were considerable near Monchegorsk. The nutrient status of the top layer of the soil has deteriorated (Fig. 32). The influence of sulphur and heavy metal emissions on soil percolation water extended to a distance of 30–40 km from the smelters (Fig. 33). However, the bedrock and overburden in the Monchegorsk region are rich in basic minerals that alleviate any acidifying deposition.

The level of microbial activity in the soil has diminished and the root systems of pine trees have become more constricted in localities 30–50 km west of Monchegorsk (Fig. 34a and b). In other words, despite the immense emissions, changes were observed only in the immediate vicinity of the pollution sources.

In Finnish Lapland, the level of microbial activity in the soil was at its lowest and the roots systems of pine trees at their smallest on nutrient-poor, lichen-dominated heathland soil sites. The grazing of reindeer contributed to this development.

Figure 34a, b. Soil respiration (a) and the time passed from glucose addition to the beginning of microbial growth (b) on the intensive sample plots along Lines #1, #2 and #3 in the humus layer of forest soils in September 1993.




Lichens are most sensitive

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Figure 35. Epiphytic lichens on tree branches and trunks and ground-dwelling lichens on the Kovdor, Kola Peninsula, intensive sample plot, 110 km west of Monchegorsk. Photo: Erkki Oksanen.

Lichens are most sensitive

Epiphytic lichens growing on the stems and branches of trees use trees only as their substrate. They are not parasitic and they do not harm the host trees. Instead, they get their nutrients from rain water and deposited dust. Epiphytic lichens are very effective in absorbing nutrients, and this is necessary for their survival and growth. Along with essential nutrients, lichens absorb many non-essential or harmful substances as well.

Lichens are the result of symbiosis between algae and fungi. The thallus of a lichen is actually a minute ecosystem in which the primary producer, an alga, and a first-degree consumer, a lichen-forming fungus, live in close interaction. The alga is able to produce carbohydrates by photosynthesis. The fungus depends on the alga for its supply of carbohydrates. The symbiotic balance between the alga and the fungus is fragile and unfavourable conditions can break it down. The more sensitive partner thus determines the fate of the lichen. Conditions favourable for one of the two can also lead to the breakdown of the symbiosis and the death of the lichen. An improvement in the supply of nutrients, for instance, may enhance the growth of the alga but be harmful to the fungal partner.

The ability to absorb harmful substances, and the fragility of symbiosis between the alga and the fungus, make lichens sensitive to air pollution. Reduction in the number of species (the disappearance of certain sensitive species), a decrease in the quantities of those surviving, and the occurrence of pollution-resistant lichens and algae help in identifying areas exposed to air pollution. Therefore, the lichen distribution studies (lichen mapping) are among the most widely used bio-indicator methods.

Pollution injuries can be observed in lichens at the cellular level long before external damage is apparent. Some conclusions on causes of the damage can be drawn on the basis of the diagnostic symptoms. This requires the use of an electron microscope and/or physiological measurements.

Epiphytic lichens are highly useful bio-indicators. In addition they are the wintertime fodder of reindeer in northern regions. Consequently, changes in the abundance or condition of lichens can have direct impacts on reindeer husbandry. Terricolous lichens are, nevertheless, the more important lichen category in this respect. The degradation of lichen pastures due to the effect of airborne pollutants or grazing by reindeer can also influence the soil's temperature and moisture conditions, microbial activity, nutrient status, and the frost-hardiness of plant roots (Figs. 36 and 37).



Erkki Oksanen

Figure 36. A view of ungrazed pine forest at Yena, the Kola Peninsula, 80 km west of Monchegorsk.



Erkki Oksanen

Figure 37. A view of pine forest grazed by reindeer at Mooseksenkuru, Salla, Finnish Lapland.

Main results

The composition of epiphytic lichen community is probably controlled by climate of the region. However, the community composition correlates with air quality as well. Assessment of air quality could be made on the basis of the epiphytic lichens on some areas in this study. While no changes in community composition were observed over large parts of the area, the species composition of the epiphytic lichens in Inari, Salla, Kemi and Tornio (in Finnish Lapland) and Monchegorsk (in Russia) indicated that air was polluted (Fig. 38a and b).

The results of membrane-leakage tests of epiphytic lichens also indicated that changes had taken place in Inari, Monchegorsk and Salla (Fig. 39). While the natural variability in the physiology of li-

chens complicated the interpretation of the results, it was apparent that the emissions of pollutants from the Kola Peninsula had caused changes in the functioning of cell membranes in lichens.

An increase in the wet and dry deposition of sulphur leads to a rise in the concentration of sulphur in lichens and to specific changes in lichen ultrastructure. The characteristic combination of symptoms was observed in epiphytic lichens throughout the Inari and Salla regions of Finnish Lapland and in the vicinity of Monchegorsk. The effects of local pollution sources in Finland were also observed (Figs. 40 and 41). Furthermore, the ultrastructure of the lichens indicated that nitrogen deposition south of Salla

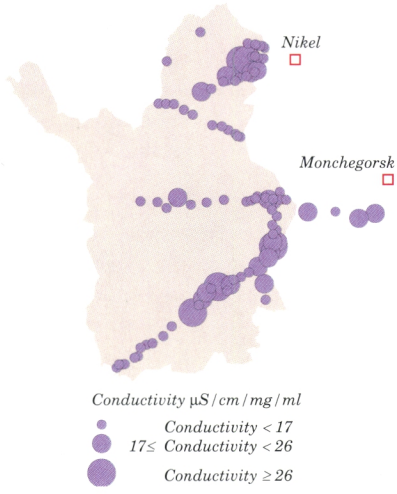


Figure 39. Average conductivity of Bryoria fuscescens per gram of dry-weight of the lichen on the Lapland Forest Damage Project's sample plots. The samples were collected in 1990 and 1991.

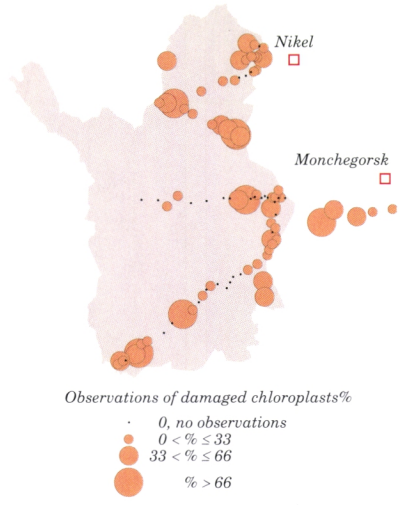
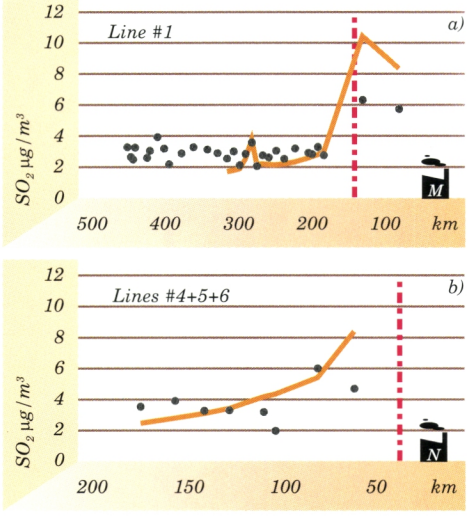
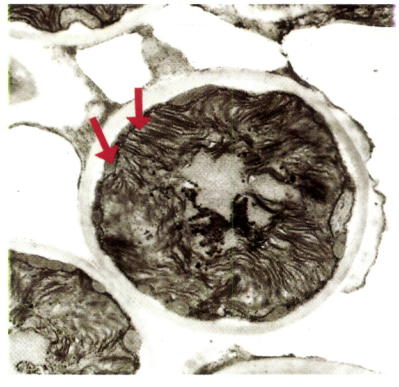


Figure 41. The occurrence of rounding of chloroplasts (i.e. a sulphur symptom) observed in Bryoria fuscescens on the sample plots of the Lapland Forest Damage Project. The samples were collected in 1990 and 1991.

Figure 38a, b. The average concentration of atmospheric sulphur dioxide along sample plot Lines #1 (a) and #4 + 5 + 6 (b) of the Lapland Forest Damage Project as predicted using the ordination analysis method (dots) and according to a model developed at the Finnish Meteorological Institute (line).





Sari Tarhanen

Figure 40. Characteristic sulphur symptoms in the algal cell of Bryoria fuscescens. The rounding in shape of chloroplast and the curling of the outer membrane (arrows) is observable. The sample was collected at Tennilä, rural commune of Rovaniemi, in September, 1991. Magnification x 6 400.

was greater than elsewhere within the study area.

The light staining of the pyrenoglobules in the chloroplasts and other associated structural changes in the vicinity of Monchegorsk constitute a hitherto unknown symptom combination. Experimental research has not yet confirmed the cause of these changes. Presumably, heavy metals or the combination of heavy metals and sulphur play a role in the development of these symptoms.

The pine stands on dry and dryish heath forests in the western parts of the Kola Peninsula clearly differ in their vegetation from corresponding sites in Finnish Lapland. Intensive grazing by reindeer in Finnish Lapland has changed the species composition of ground vegetation so much that reindeer li-

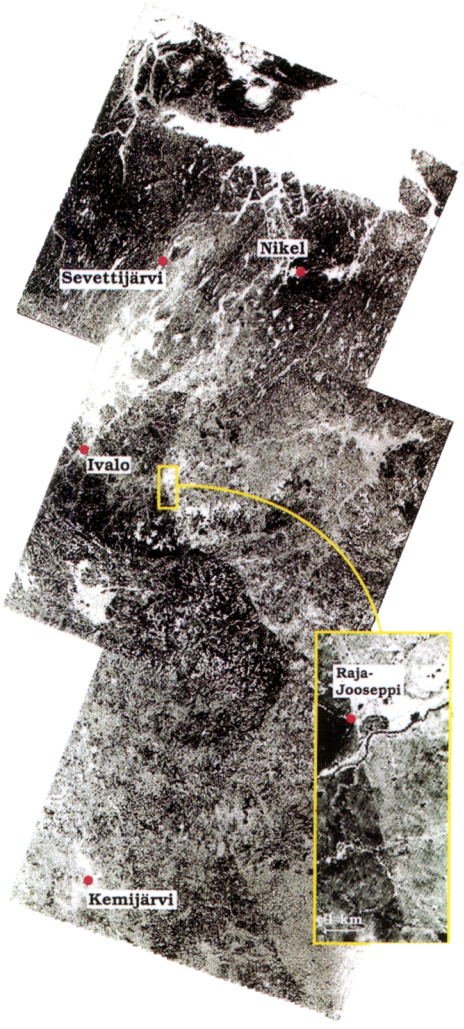
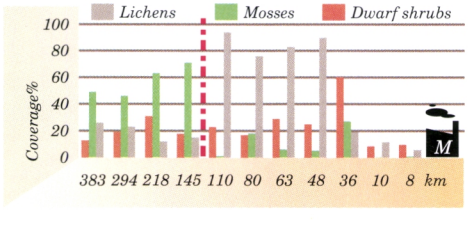


Figure 42. The grazed areas of eastern Finnish Lapland and the areas void of lichen in the vicinity of Nikel are distinguishable from the clearly lighter, ungrazed areas in the Kola Peninsula. The imagery was taken in 1987, 1990 and 1993, and it was subjected to principal component analysis. The partial enlargement shows a close-up of the effect of fences in the vicinity of Raja-Jooseppi, Inari, eastern Finnish Lapland.

chens (especially *Cladina stellaris*) have decreased in abundance and the growth space thus liberated has been invaded by mosses. The low lichen cover in Finland, compared to the Kola Peninsula, was found in analyses of satellite imagery and vegetation analyses of the lichen

Figure 43. Overall coverage of lichens, mosses and dwarf shrubs on the intensive sample plots along Line #2.

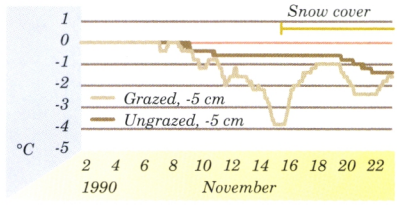


sample plots and along Line #2 (Figs. 42 and 43).

Temperature measurements conducted in Salla in 1990 and 1991 on the top layer of the soil on grazed and ungrazed lichen sample plots showed that the lichen layer clearly is an insulating mulch and that this is important especially during autumn frosts before there is a cover of snow over the ground (Fig. 44).

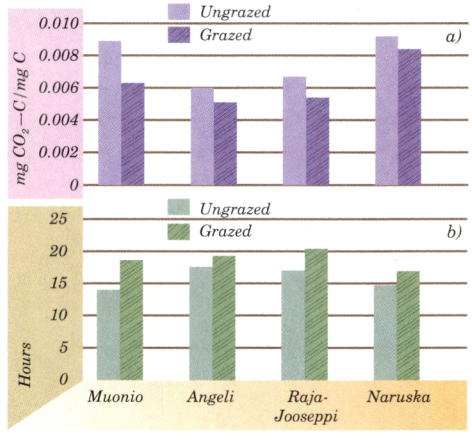
Differences in the activity of the soil microbes, and thereby in decomposition rate in the soil, were found between grazed and ungrazed lichen sample plots. The metabolic index and biomass of microbes in soils under lichen cover were at higher level and the time passed from the addition of glucose to the beginning of microbial growth at lower level compared to soils without lichen cover (Fig. 45a and b). One reason for this may be in the stability of temperature and moisture conditions due to the protection provided by the lichen cover when compared to the greater diurnal fluctuations in soils lacking this cover.

Figure 44. Soil temperature at the depth of 5 cm on the grazed and ungrazed sample plots at Naruska, Salla, eastern Finnish Lapland, in November, 1990. Midway through the month, with no snow on the ground as yet, the air temperature fell close to -30 °C.



Between September 1990 and February 1992 the frost-hardiness of the roots of pine trees on the Naruska lichen sample plots was at its lowest in September (-5 °C) and at its highest in December (-21 °C). The differences in frost-hardiness among grazed and ungrazed sample plots were not statistically significant. However, the insulating effect of the lichen cover becomes important when there is no snow and the ability of roots to withstand frost may be inadequate.

Figure 45a, b. The metabolic index (a) and time passed from the addition of the glucose to the beginning of microbial growth (b) in the humus layer of ungrazed and grazed lichen sample plots in September, 1993.






Scots pine condition
as indicated by needles

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Figure 46. Chlorotic and necrotic pollution damage in the needles of Scots pine and substitute shoots 2 km west of the Monchegorsk industrial centre. Photo: Erkki Oksanen.

Scots pine condition as indicated by needles

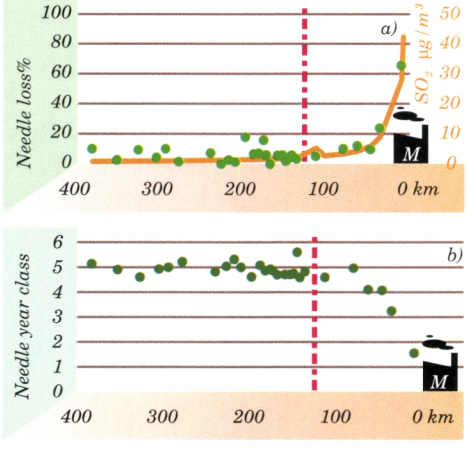
Several of the most important processes in conifers take place in their needles. Changes in the condition of conifer needles influence many other life functions in the tree and thereby the overall vitality of the tree. By studying the structure and chemical composition of needles, and the quantity and changes in the quantity of the needle mass, it is possible to make assessments of the overall condition of trees.

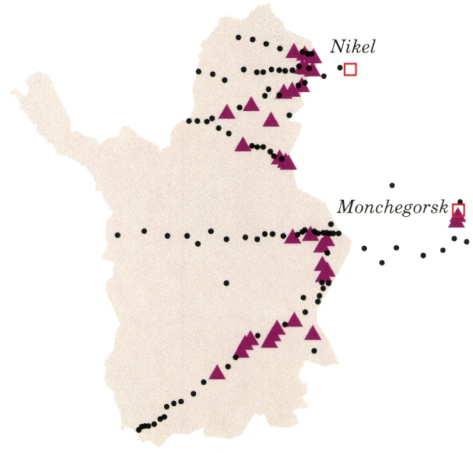
When a tree is afflicted by some form of stress, e.g. nutrient deficiency, the first stress symptoms are manifested as disturbances in metabolism. These can be identified by means of chemical and biochemical analyses. If the stress condition continues to apply or becomes more marked, changes in internal structure appear first at cellular level and later at tissue level. These changes can be studied by means of both light and electron microscopes. If the stress condition is extremely powerful or if it persists for a long period of time, external symptoms will appear. At this stage trees often resort to premature shedding of their foliage, i.e. they become defoliated to varying degree. Mostly it is only then that the forest owner awakens to the fact that such trees are in a poor state of health and the situation is serious.

By the time external symptoms appear, the trees are also afflicted by several secondary damaging agents, e.g. diseases and insects. Visible symptoms do not usually provide enough information on the actual cause. Visible symptoms are almost without exception non-reversible, whereas symptoms at the cell or tissue level, or previous to them at the chemical and biochemical level, are often reversible.

This study is an assessment of the vitality of Scots pine in Finnish Lapland and the Kola Peninsula based on examination of needle structure, the chemical composition and frost-hardiness of needles, and of the trees' needle mass and changes observed in it.

Figure 47a, b. The average needle-loss by Scots pine and the average of estimated atmospheric sulphur dioxide concentration (a), and the estimated number of needle year classes (b) in the upper part of the crowns of trees on the sample plots along Line #2 in 1991.





• *Sample plot*
▲ *Sample plot, containing ≤ 30% coverage of wax tubes*

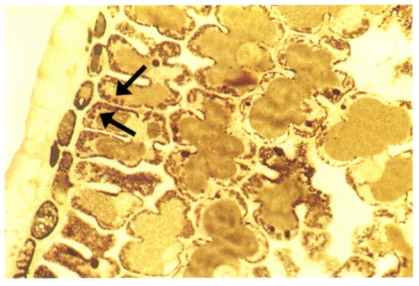
Figure 48. Those sample plots belonging to the Lapland Forest Damage Project on which the coverage of wax tubes of the stomata of one-year-old needles in 1990 was 0–30% of the wax coverage of entirely healthy needles.

Main results

Needle loss of Scots pine increased in the south-to-north direction in Finnish Lapland. In the Kola Peninsula, needle loss increased on nearing Monchegorsk; the pines were clearly defoliated within a radius of 30–60 km from the smelter (Fig. 47a and b). However, the trees close to the Nikel smelter were not very much defoliated; this may be explained by the young age of the stands. No eastward increase in defoliation nor decrease in the number of needle year classes in stands of pine was observed in Finnish Lapland.

The surface wax of one-year-old needles had been eroded or it was poorly developed. Needles

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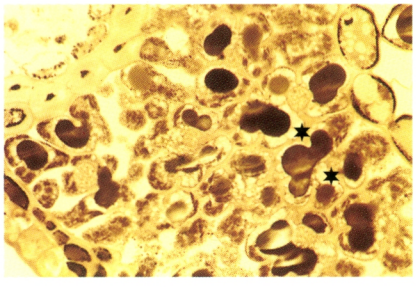


a)

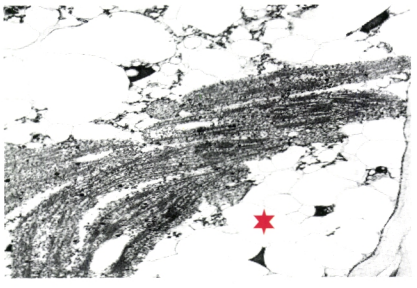


b)

Figure 49a, b. Diminished, dark chloroplasts, typical symptoms of exposure to ozone, in the mesophyll cells of a Scots pine needle (arrows). The sample was collected in October–November, 1990, along sample plot Line #1 in Finnish Lapland. Magnifications x 160 (a) and x 3 500 (b).



a)



b)

Figure 50a, b. Vesiculation of the cytoplasm, typical symptom of the effect of acid rain and/or the resultant diminished frost-hardiness, in the mesophyll cells of a Scots pine needle (asterisks). The sample was collected in October–November, 1990, along sample plot Line #6 in Finnish Lapland. Magnifications x 160 (a) and x 3 500 (b).

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on around one-third of the Lapland Forest Damage Project's sample plots had less than 30% of their wax tubes intact. These sample plots were concentrated in the vicinity of Monchegorsk and the Finno-Russian border (Fig. 48). The area of marked eroding of the wax of pine needles in Russia extended to a distance of ca. 40 km from the Monchegorsk smelter. In Finland such eroding of the wax was observed in the vicinity of Kemi–Tornio and Kemijärvi. In the Kola Peninsula the said phenomenon was observed to be around two and a half times as rapid as elsewhere on average.

The most common microscopic symptom observed was the diminishing in size and darkening in colour of the chloroplasts and the vesiculation of the cytoplasm (Figs. 49a and b, 50a and b). The vesiculation of the cytoplasm in Finnish Lapland may be the joint outcome of acid rain and the associated reduced frost-hardiness, with

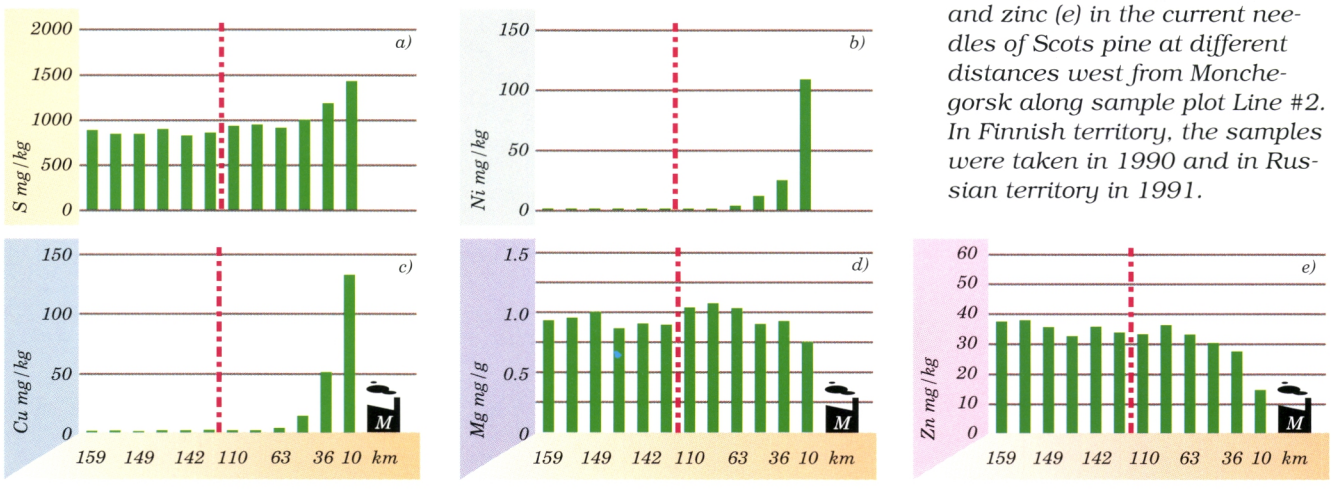


Figure 51a–e. The average concentrations of sulphur (a), nickel (b), copper (c), magnesium (d) and zinc (e) in the current needles of Scots pine at different distances west from Monchegorsk along sample plot Line #2. In Finnish territory, the samples were taken in 1990 and in Russian territory in 1991.

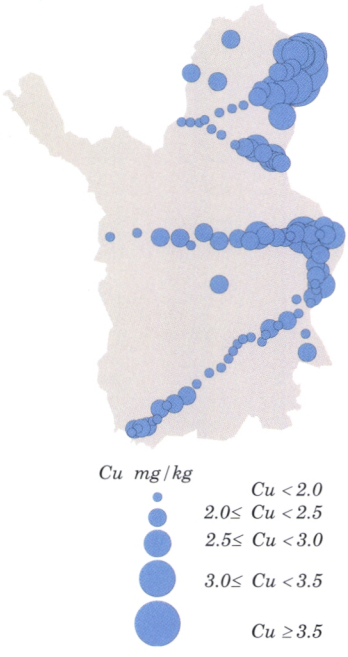


Figure 52. The average concentrations of copper in the current needles of Scots pine on sample plots belonging to the Lapland Forest Damage Project in Finnish Lapland in 1990.

the final stage consisting of the breaking down of plant cells in the Kola Peninsula. Deformation of chloroplasts was a common occurrence at a distance of ca. 10 km from the smelter. The membranes involved in photosynthesis were generally in good condition, but darkening of chloroplasts was common and the plastoglobules accumulated inside them were small and light in colour.

The impacts of the metal smelters of Monchegorsk and Nikel were manifested in the form of increased sulphur, nickel, copper, iron and aluminium concentrations in pine needles and reduced magnesium, zinc and manganese concentrations (Fig. 51a–e). These impacts were at their most powerful in the vicinity of the industrial centres. In Finland, they were manifested most clearly in the eastern parts of Inari in the form of slightly risen concentrations of sulphur, copper and nickel (Fig. 52). Apart from these changes, pine stands on the Finnish side of the border were characterised by low nitrogen and phosphorus concentrations. However, some signs of nutrient disturbances, indicating acidification of the soil, were observed. The results of analyses also showed that the higher the average of estimated atmospheric sulphur dioxide concentrations were, the higher were the foliar sulphur concentrations (Fig. 53).

The metal particles and metallic sulphur compounds originating from the smelters are transported as tiny particles along with gaseous substances and drops of water. The commonest particles found on the surface of needles in the vicinity of Monchegorsk were iron, silica, calcium, nickel, sulphur, aluminium and copper.

The impact of emissions from the Kola Peninsula on the reduction in the frost-hardiness of Scots pine needles was observed to apply to a distance of ca. 30 km from Monchegorsk (Fig. 54). However, from there to the border, no corresponding reduction in frost-hardiness was observed. The same applied to sample plots in Finnish territory – the Kola Peninsula emissions were not observed to influence the frost-hardiness of pine needles there.

Figure 53. The concentrations of sulphur in the current needles and one year older needles of Scots pine in 1990 and the average of estimated atmospheric sulphur dioxide concentration at varying distances from Monchegorsk and Nikel along sample plot Lines #2 and #4.

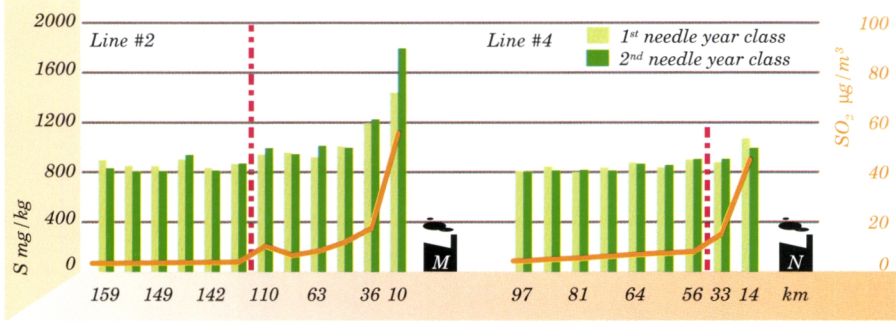
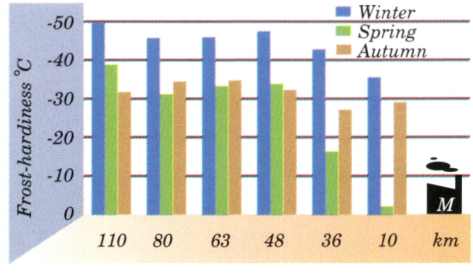


Figure 54. The frost-hardiness of Scots pine needles on the intensive sample plots in the Kola Peninsula in the spring and autumn of 1991. 10 km = Monchegorsk #2, 36 km = Imandra, 48 km = Pirenga, 63 km = Upoloksha, 80 km = Yena, 110 km = Kovdor.







Diseases and pests as additional stress factors of Scots pine

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Figure 55. A stand of Scots pine destroyed by the Scleroderris canker (Gremmeniella abietina) at Rikkilehto, Salla, eastern Finnish Lapland. Photo: Erkki Oksanen.

Diseases and pests as additional stress factors of Scots pine

In addition to being subject to harsh environmental conditions in the north, Scots pine is stressed by numerous diseases and insects. While the premature death of trees can be caused directly by abiotic factors, death is, in the end, often caused by biotic (or organic) agents. The most significant among these are the Scleroderris canker (*Gremmeniella abietina*), snow mould (*Phacidium infestans*), pine blister rust (*Endocronartium pini*), bark beetles (*e.g. Tomicus spp.*), and moose (*Alces alces*) and root vole (*Microtus oeconomus*) (Fig. 56). Damage of local significance can be caused by various needle-consuming insects such as the European pine sawfly (*Neodiprion sertifer*).

Epidemics of fungi and other harmful biotic damage agents are often preceded by weakening of tree health due to some abiotic cause. Extremes in weather conditions can weaken the ability of trees to resist pathogens, while at the same time promoting the outbreak of pests.

Different groups of pests have different requirements. Cool and humid growing seasons are favourable to fungi, whereas warm and dry summers promote the increase in numbers of many insect populations.

Changes in the environment caused by human activity can lead to changes in the relationships between plants and pathogens. Stands of Scots pine in Salla, eastern Finnish Lapland, found to be afflicted by the Scleroderris canker (*Gremmeniella abietina*) in the late 1980s aroused queries as to the possible involvement of emissions of pollutants from the Kola Peninsula in the increased occurrence of diseases. The interaction between Scots pine and the Scleroderris canker involves several kinds of interactions with both abiotic (weather, site) and biotic (microbes, insects) factors.

Erkki Oksanen



Figure 56. The top of a 12-year-old, planted Scots pine afflicted by the Scleroderris canker (Gremmeniella abietina) at Naruska, Salla, eastern Finnish Lapland, in August 1994. Symptomatic of the advance of the disease, some of the brown needles are darker in colour at the base and some are curled downwards. Another characteristic of the disease is the retardation of growth at the shoot tips.

It was decided to approach this problem by examining the history and present-day situation regarding the occurrence of the Scleroderris canker at varying distances from Monchegorsk's emission sources. Additionally, experiments involving exposing pine trees to impurities and pathogens were set up at the Kevo Subarctic Research Station and at the METLA's Rovaniemi Research Station (Fig. 57).

Main results

The cases of forest damage in Salla in the late 1980s were caused by top and shoot dieback of Scots pine following infection by the Scleroderris canker. The proportion of stands thus afflicted of the total forestry land area in eastern Lapland was very small and most of the stands were only slightly damaged. On the sample plot lines, the most severe infection by the Scleroderris canker occurred



Tarmo Virtanen

Figure 57. The effect of airborne pollutants and fertilization on the susceptibility of Scots pine seedlings to attacks by pests and infection by the Scleroderris canker (Gremmeniella abietina) was studied on an experimental field at the METLA's Rovaniemi Research Station. The seedlings were enclosed in gauze bags when raising aphids.

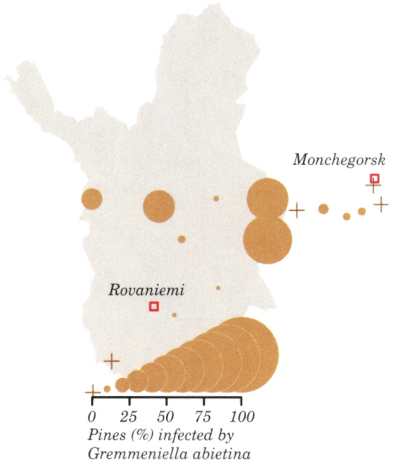
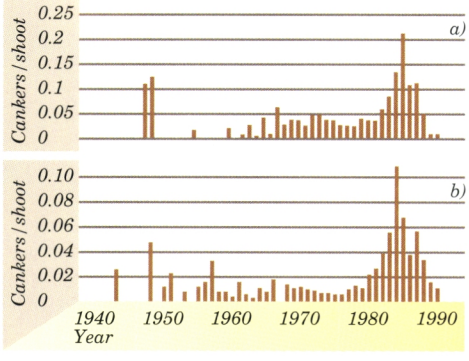


Figure 58. The relative proportions of Scots pine infected by the Scleroderris canker (Gremmeniella abietina) in 1992 and 1993 in the vicinity of the intensive sample plots along sample plot Lines #1 and #2.

Figure 59a, b. The occurrence of the Scleroderris canker (Gremmeniella abietina) on the branches of Scots pine on the basis of the relative amounts of cankers made by the pathogen at Rikkilehto, Salla, in a stand severely damaged by the fungus (a) and at Kemihaara, Savukoski, in a stand moderately damaged by the fungus (b) from the late 1930s to the 1990s.



along Line #2 from Monchegorsk to Muonio, but east-west differences were not observed (Fig. 58). In the Kola Peninsula, infections were restricted to individual trees. Infected stands were usually in depressions close to watercourses and in overstocked increment stands.

Using a branch analysis method, it was observed that the Scleroderris canker had caused damage to Scots pine in Rikkilehto (Salla) and in Kemihaara (Savukoski) already in the 1940s (Fig. 59a and b). The disease had, however, been at its worst in the 1980s. In severely damaged stands, such as those encountered in Rikkilehto, pine shoot beetles (*Tomicus spp.*), secondary invaders, left behind them skeleton forest landscapes in the late 1980s (Fig. 55).

The Scleroderris canker fungus was also observed to multiply in live pine branches and this contributed to maintaining the epidemics to be in force longer. Races of this disease, characterised by differences in symptoms, were found both in Lapland and in the Kola Peninsula.

Also experimental studies pointed out the importance of natural environmental factors in the occurrence of the Scleroderris canker. Irrigation with purified water benefited the pathogen, and this also indicates that environmental factors independent of impurities (rainwater especially) are of relevance when interpreting regional observations; e.g. along the sample plot lines (Fig. 60). Acidic and heavy metal treatments had no marked effect on the development of the Scleroderris canker.

Aphids predisposed seedlings to the Scleroderris canker (Fig. 61). Heavy-metal treatments did not have any influence on the occurrence of aphids.

The harmless endophytic fungi in the pine shoots were not able to protect their hosts from infection by the Scleroderris canker in experimental studies. Neither were these endophytic fungi any more susceptible to pollutant treatments than the Scleroderris canker fungus.

Figure 60. The occurrence of the Scleroderris canker (Gremmeniella abietina) without symptoms in Scots pine seedlings subjected to different irrigation and metal treatments.

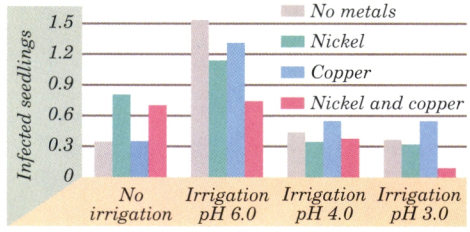
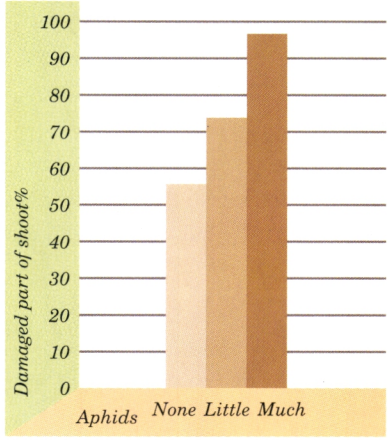


Figure 61. The effect of aphids on the Scleroderris canker (Gremmeniella abietina) infection of Scots pine seedlings. The trial comprised thirty-one seedlings.




The litter and
status of Scots pine forests

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Jarmo Poikolainen
Eira-Maija Savonen

Figure 62. Litter of Scots pine on the forest floor on the intensive sample plot of Monchegorsk #2 in the Kola Peninsula, 10 km south of Monchegorsk. Photo: Erkki Oksanen.

The litter and status of Scots pine forests

The litter plays an important role as the maintainer of the cycle of matter in the forest ecosystem and of diversity. The litter serves as the substrate for fungi, microbes and soil fauna. It is composed of the ecosystem's dying matter, comprising stemwood, branches, foliage, cones, inflorescences, roots, lichens and fauna and their faeces (Fig. 63a–e). The products of decomposition of the litter, in varying state of decay, are the constituent parts of the humus. Together with the mineral soil, the humus maintains the cycle of nutrients in the forest as a whole.

Air pollution influences the forest ecosystem in several ways; e.g. the nutrient status of the soil, vitality of trees (inc. amount of foliage and sexual reproduction), occurrence of epiphytic lichens and insects. All this is reflected in the stand litter; the state of the ecosystem can be assessed by monitoring changes in the litter. The basis for litter studies is provided by the METLA's litter material collected from different parts of Finland since the 1960s. This material is invaluable as a time series and for control purposes.

When developing environmental indicators, attention has been focused on the litter because it provides us with precise measured values to place alongside visually observable parameters in monitoring the state of the environment. When a tree becomes defoliated, it sheds above-normal amounts of foliage and branches. However, once the needle mass in the crown has become permanently reduced, the amounts of needle litter are also reduced. If a tree's ability to reproduce is impaired, the amounts of seeds and cones are reduced. The litter also enables one to monitor changes in insect populations and the amount and species composition of epiphytic lichens. In recent years, studies have focused on the amount of decaying woody material in the forest; again, litter studies enable this kind of monitoring, too.

The aim in the present study was to determine how the emissions released by the Kola Peninsula mining industry affect the quantity and quality of the litter. A further aim was to develop methods for monitoring the state of the environment. Material was collected over a period of four years (1990–1993) from the fourteen intensive sample plots located in Finnish Lapland and during one year (1992–1993) from the three intensive sample plots in the Kola Peninsula. Control data was provided by older litter sample plots, accessed for litter since the 1960s, in Kittilä and Rovaniemi rural commune.

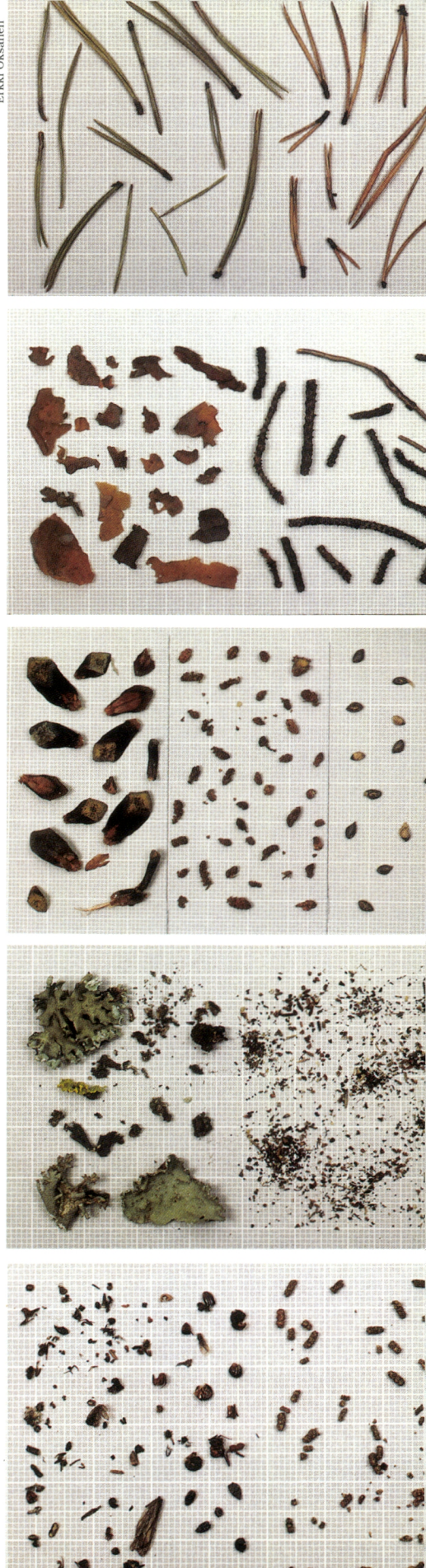


Figure 63a–e. Stand litter is comprised of the forest's dying elements: e.g. needles (a), bark and branches (b), cones, inflorescenses and seeds (c), epiphytic lichens and dust (d), and insects and their faeces (e).

Main results

Stand litter reflects a forest's state of health and fertility and the situation regarding pathogens and air pollution. When combined with other stand and environment data, the information provided by stand litter gives a good picture of stand vitality.

Air pollution causes premature death of needles and reduces their size. The number of needle year classes on pine in the Kola Peninsula was observed to have decreased some decades ago (Figs. 64 and 68). Small needles were observed mainly in the vicinity of Monchegorsk and in the needle-loss area of the summer of 1987 in Finnish Lapland (southern sample plots).

The condition of the crowns of trees in polluted areas diminishes and abnormally high amounts of needles and branches are shed. The variation in the amounts of needle and branch litter in this study is mainly explained by natural factors. The high litter amounts in Sevettijärvi and Yena, and the small amounts in Pirenga, may be caused by the emissions of pollutants from the Kola Peninsula (Fig. 65). In accordance with the results obtained in a study launched in the 1960s, there are no trend-like changes in the needle litter in western Finnish Lapland. The annual variation has been very marked (Fig. 66).

The needle-loss area of the summer of 1987 was manifested as exceptionally large litter crops, high yields of insect faeces and small needles. In Kittilä the consequences of the needle-loss phenomenon was demonstrated as exceptionally large litter crops at least during the period 1988–1991.

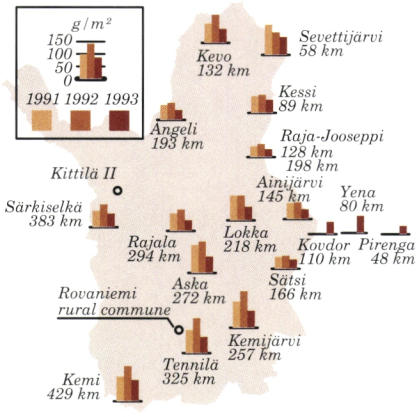


Figure 65. The annual amount of litterfall on the intensive sample plots in Finnish Lapland (1991–1993) and in the Kola Peninsula (1993). The distances to the sample plots are from Monchegorsk (for Pirenga, Yena, Kovdor, Ainijärvi, Sätsi, Raja-Jooseppi, Lokka, Kemijärvi, Aska, Rajala, Tennilä, Särkiselkä, Kemi) and Nikel (for Sevettijärvi, Kessi, Raja-Jooseppi, Kevo, Angeli). The control sample plots used were the Kittilä II litter sample plot and the litter sample plot in the rural commune of Rovaniemi, active during 1960–1992.

Figure 66. Variation in the needle litter crop at Kittilä, western Lapland, during the period 1961–1992. A single observation year extends from the beginning of August until the end of July; e.g. the year 1990 corresponds to the period 1.8.1989–31.7.1990.

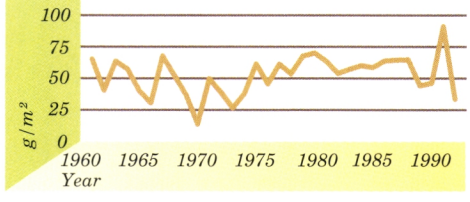


Figure 64. The long-term variation in the number of needle year classes of Scots pine on the intensive sample plots from Monchegorsk to Sätsi (Salla).

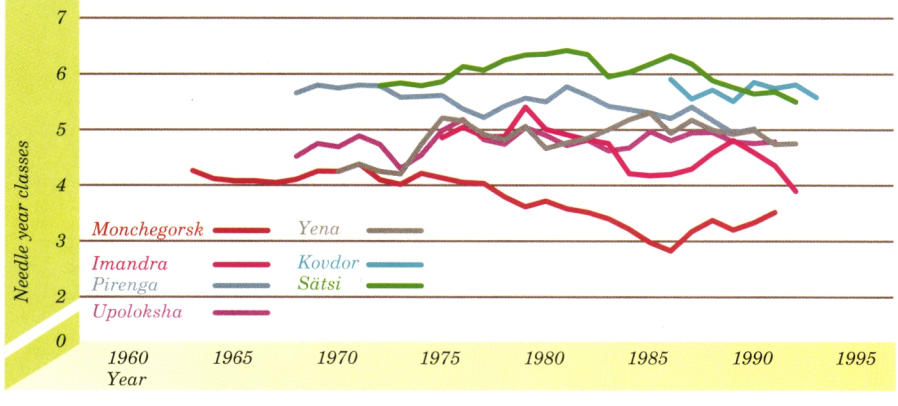
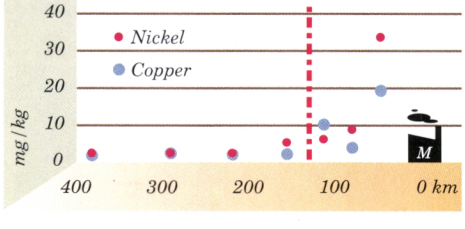


Figure 67. The concentrations of nickel and copper in the needle litter along sample plot Line #2 in the autumn of 1993.



Air pollutants impair the reproductive capacity of trees. In this study the amount and size of seeds decreased on the Russian side of the border on approaching Monchegorsk. The seed crops in western Finnish Lapland have varied a great deal since the 1960s without a distinct trend.

The amount of insect faeces is indicative of the size of the insect populations consuming the needles. The Raja-Jooseppi sample plot and southern sample plots were observed to have the highest yields of faeces. No distinct increases in insect damage to pine were observed in the vicinity of emission sources.

Air pollutants accumulate in the litter and thus increased concentrations can be recorded in areas exposed to pollution. The concentrations of sulphur and heavy metals in needles, tree bark, seeds and cones have increased in the Kola Peninsula (Fig. 67). Increased concentrations of sulphur, nickel, copper and chrome in tree bark were recorded east of Lake Inarijärvi and in the vicinity of Kemi–Tornio in Finnish Lapland (Fig. 69a–d). Elsewhere in Finland these concentrations have decreased since the peak of the 1970s.

Both natural variation and air-pollution-based variation were observed in the litter material. Effects clearly due to air pollutants were observed in Russian territory up to a distance of ca. 50 km from the pollution sources. On the Finnish side of the border, effects of air pollution were mainly observed in the Inari region, immediately adjacent to the border. Elsewhere in Finnish Lapland the variation was mainly due to natural causes.

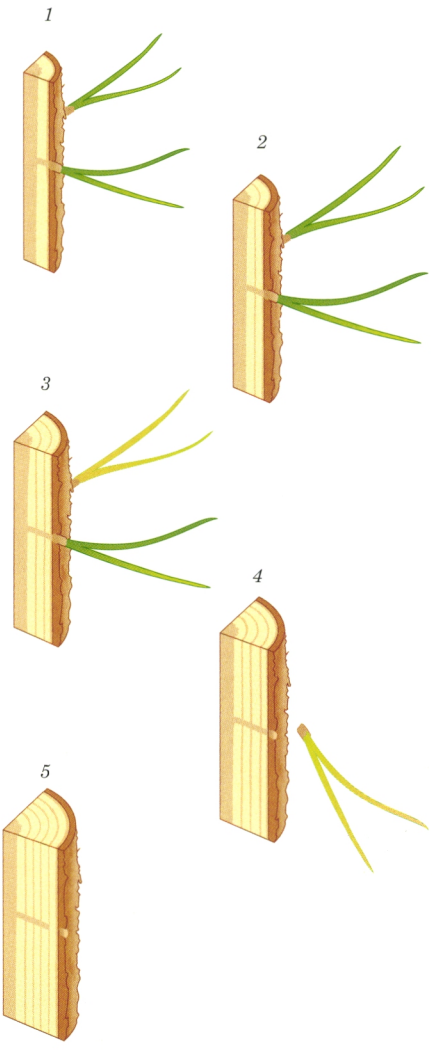
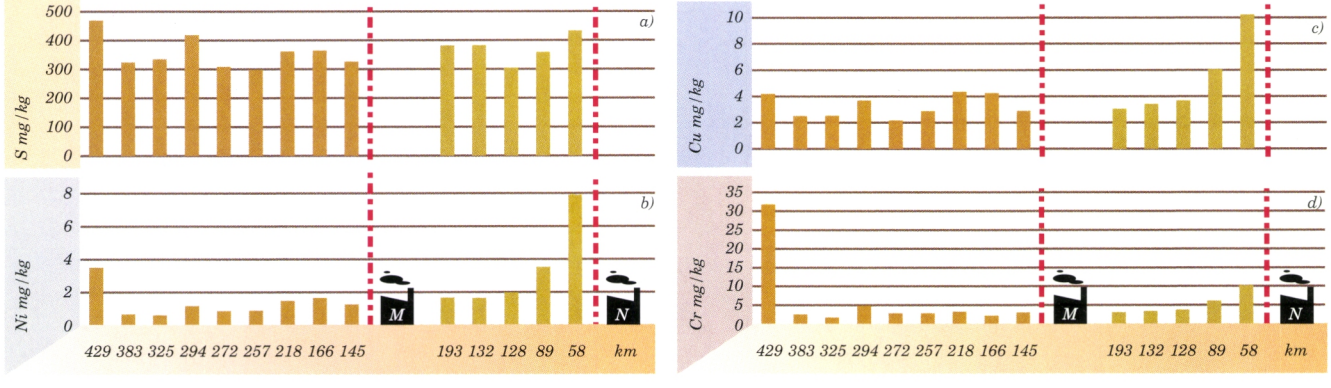


Figure 68. The long-term variation in the number of needle year classes in Scots pine is being looked into by means of the needle trace method relying on the needle traces left by needle pairs. Needle traces connect the pith and the needles and remain visible in the wood after the needles are shed. The age of the needles equals the number of annual rings penetrated by the needle trace. The needle shown in the illustration has been attached to the tree for four years.

Figure 69a–d. The concentrations of sulphur (a), nickel (b), copper (c) and chrome (d) in the bark litter on the intensive sample plots in Finnish Lapland.







Growth of Scots pine in a changing environment

Authors

Pekka Nöjd
Pekka Kauppi

Figure 70. Annual rings in a cross-section of Scots pine wood. Though the tree had died while still standing, its wood was still sound. From the Saariselkä region of eastern Finnish Lapland. Photo: Erkki Oksanen.

Growth of Scots pine in a changing environment

The ability of trees to grow and form woody tissue is an age-old property that has evolved in the course of millions of years. This is one of the most essential processes in the forest ecosystem: live and dying woody tissue maintain the forest's flow of life. In addition to being an interesting phenomenon from the viewpoint of research, tree growth is of central economic importance. Significant changes in the total growth of the forest resource result in a need for change in forest management planning and in the utilisation of forests.

Trees generally keep on growing until they die. A new germling springs forth from a seed and develops into a tree. Pines grow in height from the apical bud – as much as a metre in a year in the case of young trees. Already in July,

Erkki Oksanen

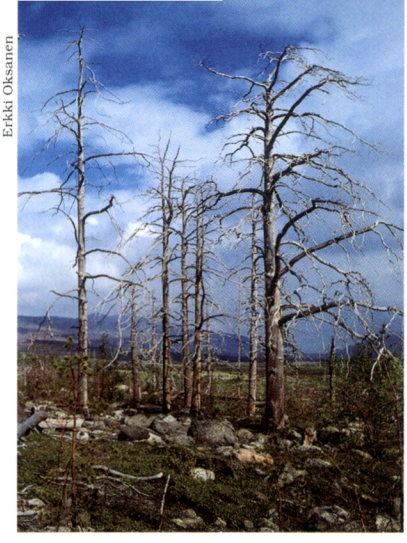


Figure 71. Live, young Scots pines in a stand of dead, still standing bigger trees, 8 km south from Monchegorsk.

shoot elongation ceases and trees form a new apical bud, ready to grow forth the following spring. Diameter growth in trees is the result of the activity of the cambium under the bark: phloem and bark tissue outwards and woody tissue inwards. As winter approaches, the cambium enters a period of rest to await the coming spring when it resumes cell division.

A conical sheath of new, usually continuous woody tissue is formed each year beneath the cambium layer of the trunks of trees. Trees also put forth new branches, foliage and roots. The various parts develop in a balanced, correct ratio. Young trees produce especially branches, foliage and roots. After a certain stage, branches begin to die and be shed. The woody tissue cells formed in the trunk are retained until the tree itself dies; in dead but otherwise sound pine "snags" these cells "survive" long after the tree has died. As trees get older, the proportion of stemwood increases.

When the Lapland Forest Damage Project was launched, it was known that there are forest-death areas, caused by pollution, in the Kola Peninsula region (Fig. 71). Forest growth in the Kola Peninsula has not been studied to any great extent – no scientific knowledge was available on changes in forest growth in the vicinity of the industrial centres. One of the goals of the project was to find out when the

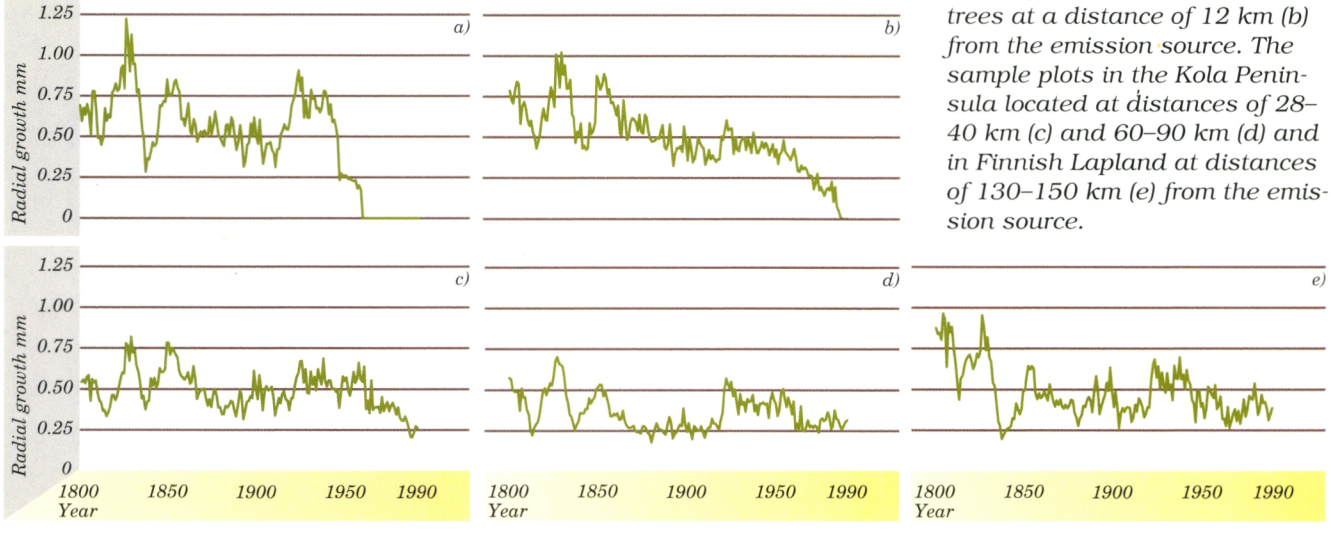


Figure 72a–e. Radial growth of old Scots pines growing at varying distances away from Monchegorsk during the period 1800–1990. The dead trees at a distance of 4.5 km (a) and the live trees at a distance of 12 km (b) from the emission source. The sample plots in the Kola Peninsula located at distances of 28–40 km (c) and 60–90 km (d) and in Finnish Lapland at distances of 130–150 km (e) from the emission source.

damage had started, how rapidly it had spread, and how far away from the industry the growth of pine had declined. Eastern Lapland was a region of particular interest: Had industrial pollution from the Kola Peninsula influenced the growth of pine in Finland, too? Yet another goal was to compare the growth phenomenon to other, more sensitive indicators of the state of the forest ecosystem. In other words, could growth be predicted with them as the basis?

Growth studies were conducted in two climatically very different regions: in eastern Finnish Lapland and in the Kola Peninsula and at the northern timber line, in Inari and northeastern Norway. A total of ca. 1 300 pines were sampled for radial growth data in different parts of Finnish, Norwegian and Russian Lapland.

Main results

The forest-death areas in the Kola Peninsula are surrounded by a zone within which the growth of pine has been below normal for the past few decades. In the Monchegorsk area growth was observed to have been reduced up to a distance of ca. 40 km south of the town (Fig. 72a–e). Other measurements, e.g. concentration of elements in needles and soil analyses, indicated that forests in these areas have been exposed to significant pollution loads.

Emissions in the vicinity of the town of Nikel have influenced the growth of pine on a clearly smaller area than in Monchegorsk (Fig. 73a–e).

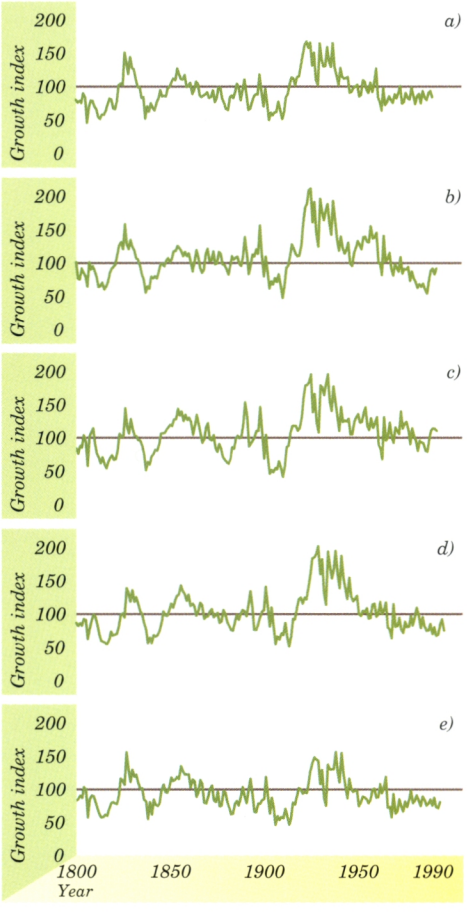
The results for eastern Finnish Lapland are encouraging. A fairly wide zone (over 50 km in width) of no retardation in the growth of Scots pine lies between the Monchegorsk damage area and the Finno-Russian border (Fig. 72d). Retardation was observed to have occurred only in areas which, according to the results obtained in the Lapland Forest Damage Project, were considerably more heavily loaded than Finnish Lapland.

The latter half of this century has been below average for tree growth throughout Lapland. However, this has also been the observation in northern Sweden. The differences in this respect between the more exposed eastern Lapland and the fairly unpolluted (as indicated by measurement data) western Lapland are minute.

In northernmost Finland, at the timber line, the growth of Scots pine in the vicinity of the eastern border in the 1980s has been slightly poorer than in western parts of the region (Fig. 73a, d and e). The differences, however, are minute. They could be the result of natural variability in growth, which in this region is quite considerable.

Thus, research failed to reveal significant changes in growth in Finnish Lapland. In the Kola Peninsula, however, the damaged areas are extensive and the damage that has occurred there is severe. Retardation in tree growth in the Monchegorsk area was observed within a radius of 30–40 km from the emission source. Only a few comparable cases of growth changes of this scope are on record to date; perhaps the best known other example is that of Sudbury, Canada.

Figure 73a–e. The growth indices for Scots pine in Inari Lapland and in north-eastern Norway at different distances from Nikel during the period 1800–1990. Western Inari 160 km (a), Svanvik (Norway) 12–15 km (b), Svanvik–Skogfors (Norway) 25–30 km (c), Sevettijärvi–Vätsäri (Inari Lapland) 70 km (d) and Kessi (Inari Lapland) 90 km (e) from the emission source.





Satellite imagery and the scope of forest damage

Author

Kari Mikkola

Figure 74. A Landsat satellite image of eastern Finnish Lapland and the Kola Peninsula. Luttojoki river flows across the top of the image, and the Saariselkä fells are on the left. The colours on the image correspond the tone range visible to the human eye. Photo: Landsat TM © ESA/1993/EURIMAGE.

Satellite imagery and the scope of forest damage

The gradient method employed in the Lapland Forest Damage Project offers good potential for the measurement and modelling of the impact and distribution of air pollutants released from point sources. The line-based system of sample plots used in the project does not, however, enable analyses of the kind possible when using mapping methods. State-of-the-art remote sensing techniques partly make up for the shortcomings of the line survey system.

Mapping satellites appropriate for the purpose of analysing vast areas are constantly orbiting the Earth and crossing over the same places at regular intervals (Fig. 75). The amount of visible light and invisible infrared radiation registered by the satellites can be analysed and interpreted by means of advanced information technology. Moreover, remote sensing enables the observation of changes that have taken place with time: the imagery produced by a particular satellite or satellite type at different points in time can be made commensurable and thereby the user is able to get a hold on the changes that have occurred at ground level. The data produced by remote sensing can be especially useful when monitoring the state of the environment.

To date, little use has been made of satellite imagery in the assessment of incidents of forest damage caused by air pollution. In terms of its scope and severity, the damage in the Kola Peninsula equals the environmental catastrophe caused by the Sudbury nickel and copper smelters in Ontario, Canada. The damage to the environment and the gradual reinstatement of flora and fauna in this area following reductions in the emissions have been the subjects of several studies in which remote sensing material has been used as an aid in mapping. Mapping of moderate damage is particularly difficult in naturally sparse forests lacking a contiguous canopy layer as the signal from the spectrum is easily lost in background interference. New methods, especially the imagery yielded by high-resolution, multi-channel scanning from an aeroplane, can be expected to considerably improve the situation.

The present study was divided into two parts. The severe cases of damage to the immediate environment in Monchegorsk were mapped using modified Landsat 5 TM scanner material applying interpretation based on unsupervised classification and interpretation of the field observations made of the classes obtained. The dynamics of damage was examined using the unsupervised classification and threshold differences of the channel relationships of multitemporal, spectrally calibrated Landsat MSS imagery.

Access to the Nikel area by foreigners has been under strict regulation. Due to lack of field observations, satellite imagery available on the area has not been interpreted. Using the extensive field support data collected in Norwegian territory and remote-sensing data, researchers there have made a thorough analysis of the damage to the vegetation in the vicinity of Nikel. In order to avoid overlapping, this study was limited to the vicinity of Monchegorsk in regard to analyses conducted in Russian territory.

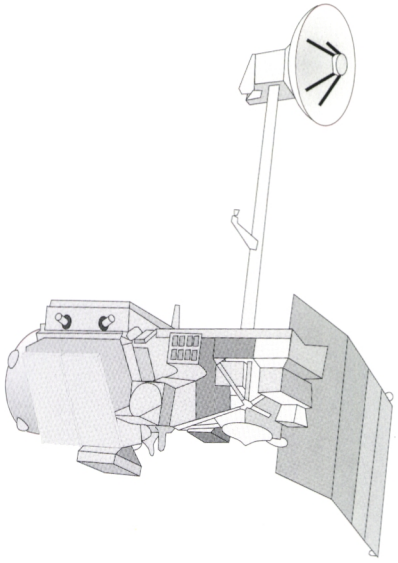


Figure 75. The LANDSAT 5 satellite was launched on 1.3.1984.

Figure 76. A slope on the Monche fells, 2 km west of the Severonikel smelter, void of vegetation and damaged by erosion.



Erkki Oksanen

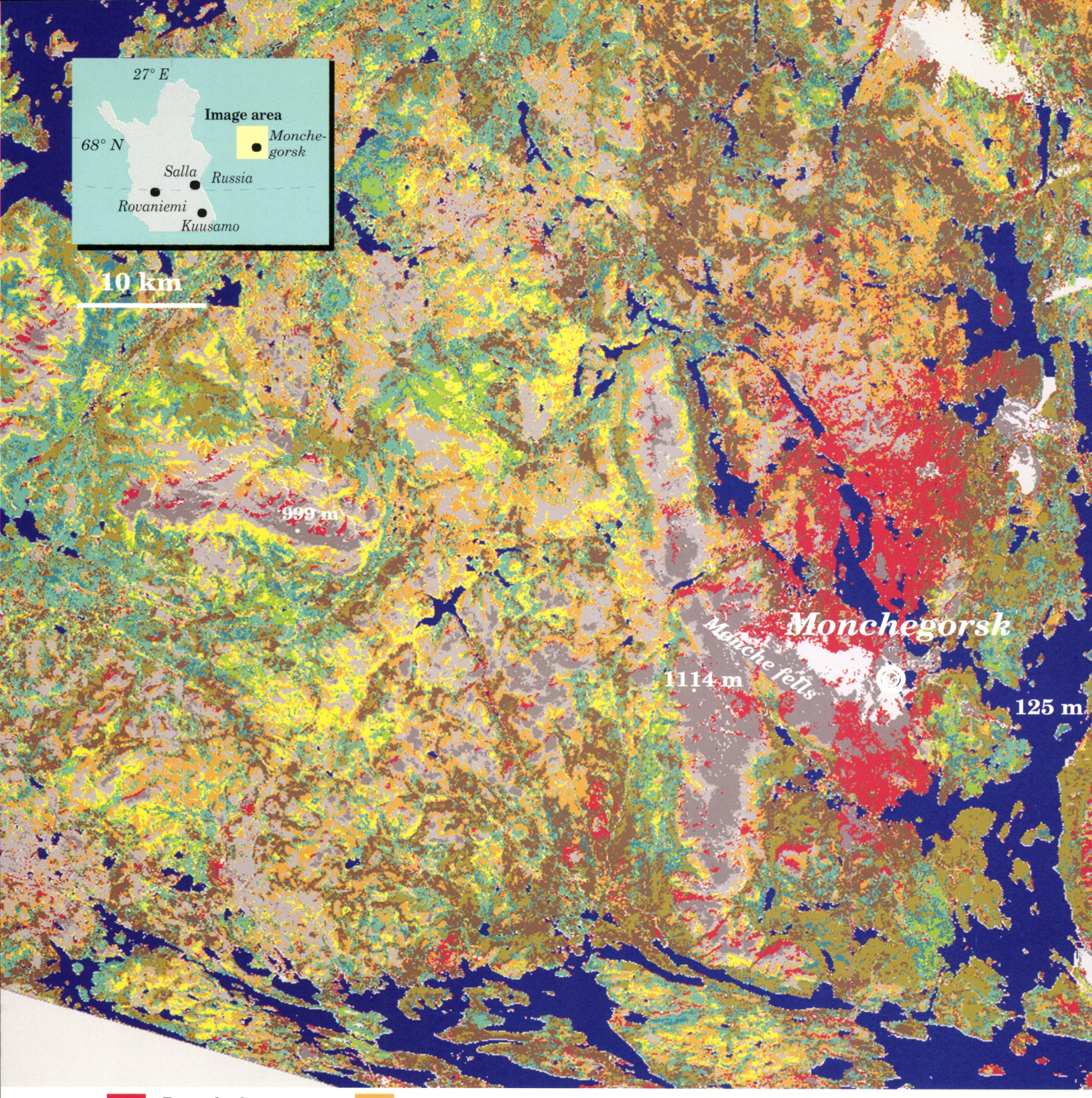


Figure 77. The state of the environment at Monchegorsk in 1985 according to the unsupervised classification used in connection with Landsat 5 satellite imagery.

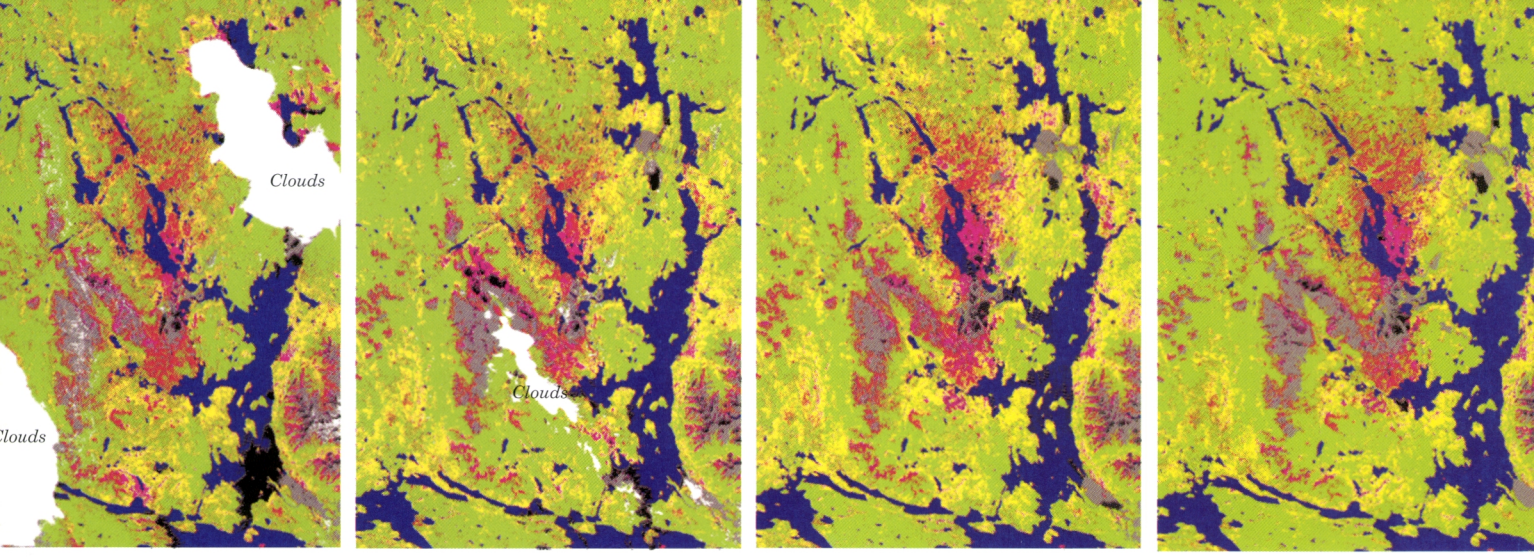


Figure 78a–d. The results of multitemporal MSS scanner material classification of the Monchegorsk area. The forest-death area shown in red has expanded during the monitoring period: 1978 (a), 1980 (b), 1986 (c) and 1989 (d).

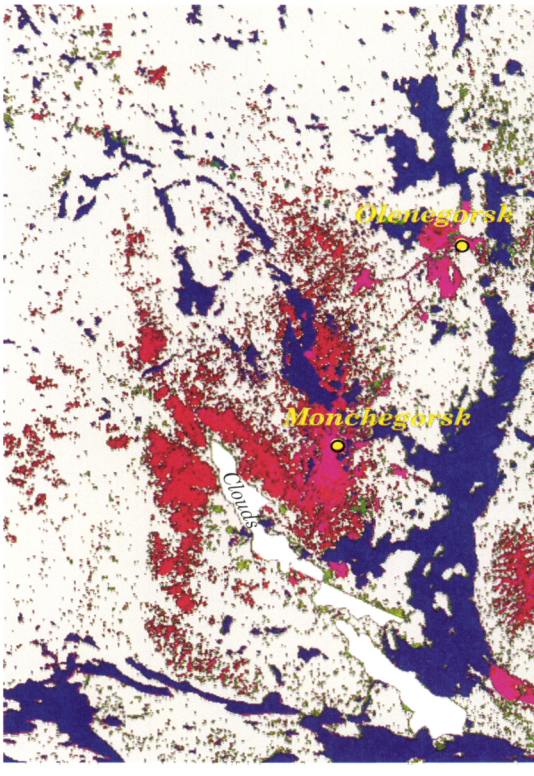
Main results

The damage areas surrounding the Kola Peninsula's large metal smelters, especially that of Severonikel in Monchegorsk, were delimited by means of satellite-imagery analyses. According to the results of interpreting Landsat 5 TM material from the year 1985, the vegetation in the vicinity of Monchegorsk had been entirely destroyed or severely damaged over an area of 40 000–50 000 ha (Figs. 76 and 77). The damage zone surrounding the forest-death area, manifested by symptoms confined to the crowns of trees, could not, however, be delimited because of lack of appropriate groundtruth data.

The area of severe damage in the vicinity of Monchegorsk had clearly expanded during the period 1978–1989 (Fig. 78a–d). Both multitemporal, calibrated Landsat MSS imagery classification results and the NDVI comparisons (based on the ratio of red light and near-red light) of this imagery material led to the same outcome (Fig. 79). It would appear that the refining of the sulphur-rich Norilsk ore in the Kola Peninsula, starting in the early 1970s, has accelerated the occurrence of severe damage in the vicinity of the smelter during the period of observation.

Remote mapping methods enable reasonably accurate and regionally reliable assessments of severe environmental damage. Analyses of damage focusing on individual forest stands, when using the currently available satellite imagery of rough resolution, are not reliable, especially when studying the sparse boreal forests. However, the rapid evolution in remote sensing technology can be expected improve the situation in the near future.

Figure 79. An NDVI difference image of Monchegorsk between the years 1980 and 1989. Degeneration of the vegetation (red colour) is clearly evident in the immediate vicinity of the smelter.







Conclusions

Author

Eero Tikkanen

Figure 80. A branch of Scots pine in flower on the Upoloksha intensive sample plot in the Kola Peninsula, 63 km south-west of Monchegorsk. Photo: Erkki Oksanen.

Conclusions

The immense emissions of pollutants and cases of damage to the environment in the Kola Peninsula were revealed to the Finnish public in the late 1980s. The concurrent incidents of needle loss by coniferous trees in Finnish Lapland and forest damage in Salla, eastern Finnish Lapland, provided grounds for suspecting some connection between these and the emissions from the Kola Peninsula. News of the damage to the environment in the Kola Peninsula and of the forest damage in Lapland began to worry forest owners and other concerned citizens. Demands began to be expressed for research efforts to be directed at determining the causes of the damage and for restrictions to be imposed on the emissions from the Kola Peninsula. The results provided by the national HAPRO project on acidification proved to be insufficient in regard to Lapland; the project's final report contains a proposal for further research focusing on Lapland and the Kola Peninsula (Kauppi et al. 1990, Kenttämies 1991).



rkki Oksanen

Figure 81. The air-quality measurement station established at Kirakkajärvi, Sevettijärvi (Inari), in 1991.

A joint, five-year project, the Lapland Forest Damage Project, participated in by four universities and five research institutes, was launched in May 1989 at the initiative of the Finnish Forest Research Institute (METLA). The project's primary goal was to report on the impact of the emissions of pollutants from the Kola Peninsula on the forests of Finnish Lapland. Secondly, the project endeavoured to pinpoint and delimit the areas of forest damage in the Kola Peninsula. The third goal was to produce basic scientific knowledge on the environment in Lapland and the changes taking place in it.

The METLA established an extensive, line-based sample plot system covering all of Finnish Lapland and part of the Kola Peninsula. The sample plots were located in dry and dryish heathland forests, which were assumed to be sites sensitive to acidification. The results of watercourse studies conducted by the Lapland Water and Environment District gave reason to suspect that acidification may also be threatening the forests of Lapland (Kinnunen 1990, 1992). All the field measurements and collecting of data for laboratory analyses were concentrated on common forest stand sample plots. A station for recording air quality, important from the point of view of the project, went into operation in Sevettijärvi (Inari) in 1991 (Figs. 81 and 82).



Erkki Oksanen

Figure 82. The analysator and light source of the DOAS device for recording gaseous impurities in the air at the Sevettijärvi measurement station.

Air quality and deposition

Sulphur dioxide and heavy metals

The most typical characteristic of the pollution climate in Finnish Lapland is in the occasional rises in the concentrations of atmospheric sulphur dioxide to fairly high levels when the winds blow from the north-east or east, where the Kola Peninsula's industrial centres lie. This is to be observed in the eastern parts of Inari and in parts of eastern Finnish Lapland, where peaks occur at fortnightly intervals on average. The highest concentration of atmospheric sulphur dioxide was recorded at Sevettijärvi in July, 1992, when it was 500 $\mu g/m^3$. Since then, the highest concentrations there have varied between 150–300 $\mu g/m^3$. Moreover, the concentrations of nickel and copper in the air rise significantly during north-easterly and easterly winds. The pollution episodes originating from the Kola Peninsula also manifest themselves in the air over western Lapland, but diluted to 1/10th of the concentrations in eastern Lapland. Indeed, west-

ern Lapland has the cleanest background air in all of northern Europe.

Despite the occasional concentration peaks, and with the exception of the small part in eastern Inari, the average of estimated atmospheric sulphur dioxide concentration in Finnish Lapland is low. In most of Lapland, the average sulphur dioxide concentration is below 2 µg/m^3, with higher values occurring eastwards.

In parts of Inari and eastern Finnish Lapland the influence of sulphur was manifested as changes in the physiology and microscopic structure of epiphytic lichens and in their species composition (Tarhanen et al. 1995). The pollution impact also manifested itself in the form of damage to the microscopic structure of Scots pine needles and increased sulphur, nickel and copper concentrations in the needles and bark (on tree trunks and in the litter) of Scots pine and in mosses (e.g. Raitio 1992, Sutinen & Koivisto 1992, Turunen et al. 1994).

Acidifying deposition

The acidity of the deposition in Lapland is regulated by the sulphuric acid formed from sulphur dioxide. Oxides of nitrogen have little significance in the acidification process. As a whole, the annual acid deposition in Lapland is moderate, around half of that in southern Finland. This is mainly due to the lower precipitation in northern Finland. Moreover, part of the precipitation comes down as snow and sulphur dioxide is not readily bound to it. Since the rains are generally brought in by southerly winds, the proportion of sulphur from the Kola Peninsula in the wet deposition is small. All in all, only a very small fraction of the Kola Peninsula's sulphur dioxide emissions is transported to Lapland as wet deposition.

Atmospheric sulphur dioxide also accumulates on vegetation as dry deposition. The amount of dry deposition is proportional to the concentration of atmospheric sulphur dioxide. Since high concentrations of sulphur dioxide in the Inari region of Lapland occur during the growing season as well, the accumulation of sulphur dioxide can be assumed to have a major role in the region's overall pollution load. Calculations have indicated that over 60% of the sulphur deposition in the Inari region may come down as dry deposition. Norwegian researchers estimate 55–75% of Finnmark's (in northern Norway) sulphur dioxide emissions, originating from the Kola Peninsula, to come down as dry deposition (The Norwegian monitoring... 1986).

There is a possibility that dry deposition of sulphur dioxide will not lead to the acidification of the soil. This is supported by the throughfall measurements made in connection with the Lapland Forest Damage Project. Soil studies have not revealed significant acidification; the only changes observed were in the immediate vicinity of Monchegorsk's Severonikel nickel-copper smelter. The only signs pointing to acidification of the soil in Finnish territory were observed in the eastern parts of Inari, a region affected by pollutant emissions from the Pechenganikel nickel-copper smelters in Nikel and Zapolyarnyy. The acid-rain symptoms observed in the microscopic structure of Scots pine needles north of Lake Inarijärvi may be due to dry deposition on wet surfaces.

Ozone

The concentrations of ozone in the air over Lapland are high, equal to those recorded over southern Finland. Lapland's high, at maximum 100–150 µg/m^3, concentrations of ozone (levels which have demonstrably caused damage to vegetation in experimental conditions) are not caused by pollutant emissions from the Kola Peninsula. The emissions of nitrogen oxides and carbohydrates in this region are insufficient for ozone to be formed. The highest ozone concentrations have been measured in the late spring and beginning of the growing season, times of the year when the airborne pollutants that have accumulated in the atmosphere over the winter begin to form ozone as more and more solar radiation becomes available. Ozone is also transported to Lapland from the industrial centres of Central Europe.

There is but little knowledge available on the disturbances to the metabolism of plants and damage to plant microscopic structure caused by ozone in environmental conditions such as those in Lapland. Comparisons made to data from abroad do, however, indicate that exposure to ozone may damage plant life in Lapland. Damage to microscopic structure indicative of ozone-induced damage and the combined impact of ozone and emissions of pollutants from the Kola Peninsula were,

indeed, identified in the cells of needles of Scots pine in Finnish Lapland (Sutinen & Koivisto 1992). There is little information available on the sensitivity of boreal forest flora to ozone. The concentrations used in exposure trials are generally too high for the long-term effects of ozone to be revealed (Väre et al. 1993).

Forest-death area and damage zones

The Monchegorsk forest-death area caused by the emissions of pollutants from Severonikel was mapped using satellite imagery. Zones of visible and non-visible damage were roughly outlined in the Kola Peninsula and Finnish Lapland on the basis of field measurements and field samples. The average of estimated atmospheric sulphur dioxide concentrations, calculated using a model developed as a joint effort between Finnish and Russian scientists for depicting the distribution of emissions from the Kola Peninsula, were used in delimiting the areas (Tuovinen et al. 1993). The said zones were also delimited in the vicinity of Nikel, where field studies could not be done in connection with the Lapland Forest Damage Project.

Forest-death area

The Monchegorsk forest-death area amounts to 40 000–50 000 ha in size. It extends ca. 10 km to the south and ca. 15 km to the north of the town (Fig. 83). The area does not extend very far west because the Monche fells are in that direction. In the east there is Lake Imandra and beyond it the town of Apatity and its industrial plants. The environmental impacts of the various industrial plants combine on the western shore of Lake Imandra. The average of estimated atmospheric sulphur dioxide concentration arrived at within the forest-death area exceeds 40 µg/m^3.

Blowing mainly from the south-west and west, the winds carry the majority of Pechenganikel's pollutants to the north-east and east. Located on the timber line, Nikel's damage area is oriented from the south-west to the north-east and it is greater in area than the Monchegorsk forest-death area (Fig. 83). In addition to being influenced by airborne pollution, the size of the damage area has also been affected by an epidemic of autumnal moths (*Oporinia autumnata*), which denuded mountain birch in the region in the late 1960s.

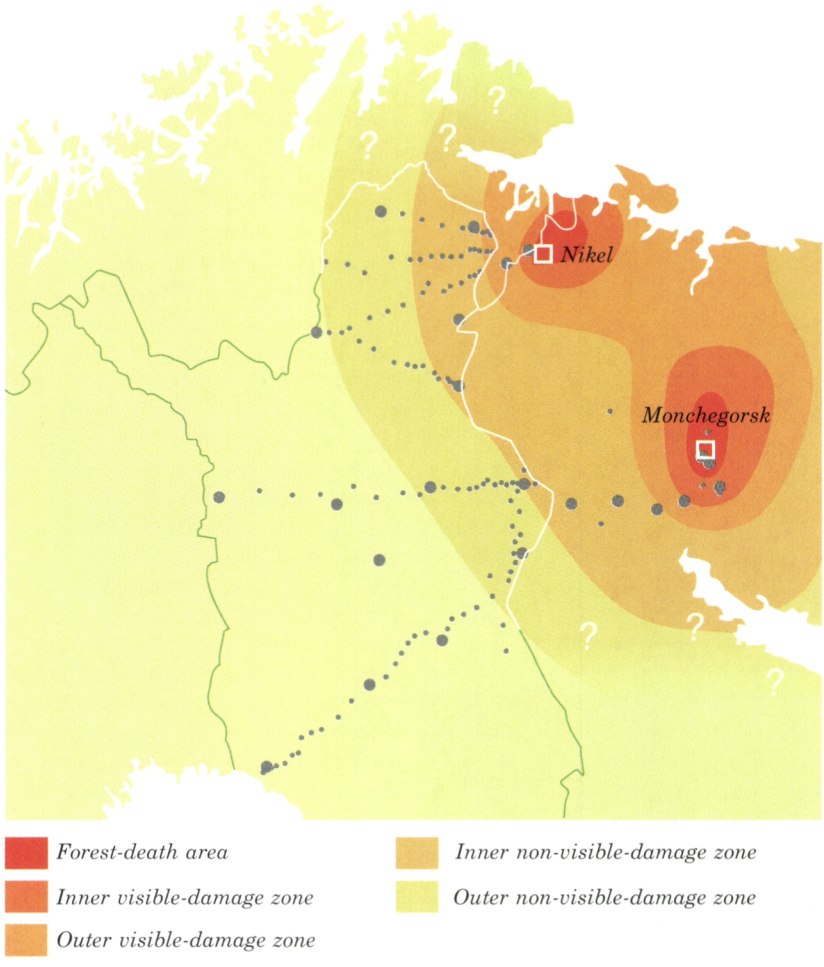


Figure 83. The forest-death areas in the vicinity of Monchegorsk and Nikel and the visible-damage and non-visible-damage zones in the Kola Peninsula and Finnish Lapland.

Inner visible-damage zone

The inner visible-damage zone extends ca. 30 km south and ca. 40 km north of Monchegorsk (Fig. 83). The conifers within this zone show marked defoliation and there are no epiphytic lichens to be seen (Fig. 84). Due to the prevailing southerly and northerly winds and the Monche fells, which rise to over 1 000 m a.s.l., this inner visible-damage zone extends no further than ca. 25 km west of the emission source (Fig. 85). The average of estimated atmospheric sulphur dioxide concentration for the inner damage zone is 15–40 µg/m^3.



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Figure 84. Severely defoliated pines ca. 30 km south of Monchegorsk. The crowns of the trees are more defoliated on the side facing the Severonikel metal smelter.

The inner visible-damage zone surrounding Nikel's forest-death area extends into Svanvik, north-eastern Norway, in the south-west (Fig. 83). Protected by the prevailing winds, Svanvik lies at a distance of only 15 km from Nikel. Since there are very few trees close to the timber line, delimiting the inner visible-damage zone is more difficult in the vicinity of Nikel than in the vicinity of Monchegorsk.

Outer visible-damage zone

The outer visible-damage zone extends to a distance of 50–60 km south and north of Monchegorsk (Fig. 83). The impact of pollution emissions within this zone is manifested as changes in the species composition of the lichen communities and external damage symptoms on the needles of Scots pine (e.g. necrosis in the tips of needles). The pollution effect, taking the form of reduced frost-hardiness of pine needles, slight slowing down of growth of pine, and chemical and microbiological changes in the soil, and reduced size of pine root systems, ceases to apply within the outer visible-damage zone (e.g. Lindroos et al. 1995, Sutinen 1995). The same applies to the effect manifested as changes in the amount and composition of the litter (Merilä & Jukola-Sulonen 1995). The marked eroding of the surface wax of pine needles extends to this zone. The average of estimated atmospheric sulphur dioxide concentration within the zone is 8–15 µg/m^3 and the deposition figures for heavy metals are high.

The outer visible-damage zone in Nikel extends into Finnish territory, to the eastern parts of Inari (Fig. 83). The combined area covered by the two types of damage zones surrounding Monchegorsk and Nikel is estimated to amount to 39 000 km^2.

Inner non-visible-damage zone

The inner non-visible-damage zone extends into Finnish territory, to northern Salla and eastern Inari (Fig. 83). Chlorosis of the stomata of pine needles is the visible needle-damage symptom manifested within this zone. The pollution effects of risen concentrations of sulphur, nickel and copper in pine needles, bark and mosses terminate within the inner non-visible-damage zone (e.g. Raitio 1992). The same applies to the pollution effects manifested as changes in the species composition of epiphytic lichens and in the physiological functions of lichens (Tarhanen et al. 1995). The effect of premature needle loss by pine terminates within Russian territory (Salemaa et al. 1992). The occurrence of occasional peaks in the concentrations of atmospheric sulphur dioxide terminates in Finnish territory within this zone. The average of estimated atmospheric sulphur dioxide concentration for the inner non-visible-damage zone varies between 4–8 µg/m^3.

Figure 85. The Monche fells, rising to over 1 000 m a.s.l. in places and located west of Monchegorsk, limit the westward transportation of pollution emissions from the Severonikel metal smelter. The photo was taken on 29.6.1994.



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Outer non-visible-damage zone

The outer non-visible-damage zone, entirely in Finnish territory, extends from the western parts of Inari to Salla (Fig. 83). The impacts of pollution within the zone are slight and local in character. They are manifested as changes in the microscopic structure of pine needles and epiphytic lichens, and as risen conductivity and decreased pH values of the bark (Poikolainen 1992). Chlorosis of pine needle stomata occurs in places. The average of estimated atmospheric sulphur dioxide concentration for the zone varies between 2–4 $\mu g/m^3$.

The effects of local emission sources (of Kemijärvi, Sodankylä, Rovaniemi and the Kemi–Tornio region) are manifested beyond the outer non-visible-damage zone; e.g. in pine needles and epiphytic lichens.

Damage process

Growth studies have revealed that the death of Scots pine in the Monchegorsk region began in the early 1950s. Tree death was preceded by progressively decreasing growth vigour and its eventual termination. With their growth at standstill, the trees may have remained alive for some years. Studies show that the forest-death area has steadily expanded and continues to do so. Tree growth has ceased and trees have died during unfavourable growing seasons, especially when the temperatures have been abnormally low.

Pollution stress

The concentration of atmospheric sulphur dioxide over the vicinity of Monchegorsk can occasionally exceed 10 000 $\mu g/m^3$. Sulphur causes damage to foliar tissues, affects the metabolism of trees, and accelerates their decline and eventual death. The pollution load also increases the sulphur concentration in the humus in the Monchegorsk area.

The majority of Severonikel's emissions of heavy metals is deposited within a radius of 40 km from the smelter. Similar observations have been made in the surroundings of the Sudbury nickel-copper smelters in Canada (Hutchinson & Whitby 1974). Heavy metals play a decisive role in the Monchegorsk region's forest-death phenomenon. Metal cations invade the exchange places of base cations (e.g. Ca^{2+}, Mg^{2+} and K^{+}) on the surface of soil particles. As a result, the soil's base saturation degree and the amount of base nutrients decrease. These in turn hinder the uptake of nutrients by plants and lead to nutrient deficiency. The magnesium concentrations in the pine needles in the area are especially low (Raitio 1992).

Heavy metals also promote forest death in the Monchegorsk region by damaging the roots of trees and by inhibiting the activity of soil microbes. Inhibition of microbial activity slows down the cycling of nutrients and reduces their availability to plants. Damage to the root systems also hinders the uptake of nutrients by plants.

There is little knowledge about the damage caused by heavy metals to the above-ground parts of plants. The concentrations of heavy metals in the foliage seldom have time to reach toxic levels.

Natural stress factors

The manifestation of damage due to pollution and the actual death of plants are often promoted by powerful natural stress factors. The foremost stress factors in boreal ecosystems are connected to climate. In the case of the vicinity of Monchegorsk, for instance, the death of trees was at its most pronounced in the 1960s, a decade of particularly unfavourable weather.

The frost-hardiness of pine needles has been reduced in the vicinity of Monchegorsk to a distance of over 30 km from the Severonikel smelter (Sutinen 1995). The accumulation of airborne pollutants on the above-ground parts of plants causes frost-hardiness-reducing changes in cell structure and functions. The late winter is the most critical time of the year because the diurnal variation in temperature is at its maximum then. Reduced frost-hardiness in plants is accompanied by reduced drought-resistance. The drought stress can also have a serious impact on plants in the late winter.

The damage process in Monchegorsk

The results of studies delving into the growth of Scot pine give grounds for concluding that forest death in the Monchegorsk region will continue to advance

at the annual rate of ca. 0.5 km. The highest concentrations of atmospheric sulphur dioxide and the maximum deposition of heavy metals occur within the forest-death area and the inner visible-damage zone, whose boundary is estimated to advance in pace with the boundary of the forest-death area. South of Monchegorsk, especially the inner visible-damage zone has expanded in the course of this project.

The results of growth studies and interpretation of the satellite imagery indicated that the forest-death area and the inner visible-damage zone expand in patches, not as a contiguous front (Mikkola 1995). The manifestation of the various forms of damage is influenced by natural factors; e.g. climate and site (plants in moist depressions endure pollution loads longer than plants at higher elevations).

The soil of the forest-death areas has been badly spoiled and erosion causes further damage on slopes. The accumulation of heavy metals in the soil is an important damage factor. It will take a long time for the ecosystems to recuperate even if emissions were to be reduced or even cease for the most part (Hutchinson 1980). The good news is that the further spread of the damage would be halted.

State of health of Lapland's forests

The studies conducted within the framework of this project did not indicate a direct connection between the emissions of pollutants from the Kola Peninsula and the incidents of forest damage observed in Finnish Lapland in the late 1980s. The primary reason for the marked premature shedding of needles during the summer of 1987 is believed to be nutrient deficiency caused by root damage resulting from the abnormal conditions of the winter of 1986–1987 (Tikkanen & Raitio 1990a, 1990b, 1990/91, 1993). Forest damage in northern Salla is attributed to top dieback caused by the Scleroderris canker fungus (*Gremmeniella abietina*) (Kaitera & Jalkanen 1992, 1994a, 1994b, 1995a, 1995b, Kaitera et al. 1995a, 1995b). The occurrence of the Scleroderris canker was not found to be connected to air pollution. Needle loss by Scots pine, especially in the Inari region of Finnish Lapland, has varied from year to year without any distinct trends (Lindgren & Salemaa 1994). Studies employing the needle-trace method and long-term monitoring of pine needle litter indicate that there is great year-to-year variation in the number of needle year classes carried by Scots pine. This variation is mainly due to changes in the macro-climate (Jalkanen 1995a, 1995b, Jalkanen et al. 1995).



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Figure 86. Damage to pine foliage caused by pine sawflies (Neodiprion sertifer) in the Saariselkä fell area.

The results of studies conducted in eastern Lapland indicate that the soil's microbial activity has diminished. The reason for this was found to be in the wearing out of the lichen layer because of grazing by reindeer. The ungrazed stands of pine in the Kola Peninsula are covered by a thick layer of lichens beyond the outer visible-damage zone. This protective layer is missing in Finnish Lapland (Väre at al. 1995). The layer of lichens evens out the soil's temperature and moisture conditions, promotes microbial activity in the soil, and most probably it also has a positive influence on the nutrient status of the soil and the frost-hardiness of roots. The marked eroding of the surface waxes of pine needles in eastern and northern Lapland may also be connected to the wearing away of the lichen layer.

In the course of the project, the researchers' attention was drawn from northern Salla to the Inari region of Finnish Lapland, which is closer to the Kola Peninsula emissions. Due to its greater pollution load and more northerly location, the forests of the Inari region are under greater threat. The effects of pollution are more numerous in the eastern parts of Inari. Finland's highest concentrations of atmospheric sulphur dioxide have been measured here and the region's copper and nickel depositions are higher than anywhere else in Finnish Lapland.

The vitality of the forests in Finnish Lapland is subject to variation: the needle-loss symp-

tom of the late 1980s has receded, but the weather conditions of the early 1990s suggest that the Scleroderris canker fungus cause increasing damage in the near future. Pine sawflies (*Neodiprion sertifer*) cause local damage in areas such as the Saariselkä fells (Fig. 86). Autumnal moth (*Oporinia autumnata*), an insect that caused severe damage to mountain birch in the 1960s in Lapland, has reappeared and caused damage in several places in western and central Lapland (Jalkanen & Nikula 1993) (Fig. 87). Only a small area in eastern Inari is under direct and immediate threat of being damaged by pollution. Apart from this, the emissions from the Kola Peninsula are not expected to cause significant damage to forests in Finnish territory.



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Figure 87. Autumnal moths (Oporinia autumnata) caused a major eco-catastrophe in the late 1960s by eating the foliage of mountain birch midway through the growing season. Ca. 500 000 ha of mountain biech in Fennoscandia suffered damage of varying degree. The photo was taken in 1970 on the shore of Shirra lake, Utsjoki, in northernmost Finland, looking west.

The emissions of pollutants from the Kola Peninsula represent a stress factor for forests in Finnish, Norwegian and Russian Lapland, and for the arctic ecosystems in general (Nenonen 1991). The vicinities of the industrial centres in the Kola Peninsula are among the world's most polluted areas (Sulphur 1994). Arctic ecosystems with their few species are highly sensitive to disturbances. Pollution loads that have accumulated there over the years inevitably lead to the toppling of the ecological balance that has evolved over the millennia. The required reduction in emissions can be realised only through the refurbishing of the Kola Peninsula's metal smelters.

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Vesa Nivala:

Figs. 18, 19

The Kola Peninsula's immense emissions of pollutants and vast areas of damage to the environment came as surprises to the Finnish public in the late 1980s. It was believed at the time that these emissions may be connected to incidents of needle-loss by Scots pine and the forest decline observed in Salla, eastern Finnish Lapland. The Lapland Forest Damage Project was launched in 1989 with the mission of studying what was happening.

This publication is the five-year project's final report in English. It is based on a more comprehensive final report written in Finnish and published in March, 1995. The book presents the central research results obtained by fifty researchers and other experts. The results presented give the reader a concise view of how the Kola pollution emissions influence the forests in Finnish Lapland, of the scope of forest-death areas, of the expansion of the damage zones in the Kola Peninsula, and of the current state of health of the forests in Finnish Lapland.

The numerous, colour illustrations and photographs provide further support for the articles based on research data. This is a book that will appeal to all who share an interest in the state of Lapland's nature and forests.