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Trends in sulphate deposition on the forests and forest floor and defoliation degree in 16 intensively studied forest stands in Finland during 1996–2003

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Deposition samples (bulk deposition, stand throughfall) were collected in 8 Norway spruce and 8 Scots pine stands throughout the year in Finland during the period 1996–2003. Defoliation was also estimated annually in the same stands. Sulphate deposition in Finland during the period 1996–2003 decreased, the decrease being most evident at the beginning of the period. Sulphate deposition in the northern part of the country has been considerably lower than that in the southern part of the country, and therefore the decrease during the period 1996–2003 in the northern part of the country has been relatively insignificant. In the eastern part of Finland, which receives a considerable proportion of the sulphate deposition from the St. Petersburg area and the shale-oil power stations in NE Estonia, there were no clear decreasing trends in sulphate deposition. The decrease in sulphate deposition elsewhere in the country was mainly due to the decrease in the sulphate concentrations since the amount of precipitation did not decrease during the monitoring period.There was a clear decreasing gradient running from southern to northern Finland in the net-throughfall of sulphate from the tree canopies in both the spruce and pine stands. No clear decrease was observed in defoliation on any of the plots during the study period, although sulphate deposition decreased significantly during 1996–2003. Sulphate deposition alone is not, at current levels in Finland, likely to cause changes in forest health in terms of defoliation in the short term at least.

Introduction

The threat posed by acidifying deposition (both nitrogen and sulphur) to forest ecosystems has been widely recognized during the past two decades, and the monitoring of sulphur and nitrogen deposition on the forests has played an important role in determining and predicting the effects of acidifying deposition on the functioning of forest ecosystems. During the past decade, the Pan-European ICP Forests Level I and II networks have made a major contribution to this work. Now, 25 years after the ratification of the Convention on the Long-Range Transboundary of Air Pollutants (CLRTAP), we have the opportunity to estimate the effects of reductions in pollutant emissions, especially of sulphur compounds, on the annual sulphur deposition on forests during the past decade.

Monitoring the level of sulphur deposition on forests ecosystems cannot be performed merely by monitoring sulphur deposition in the open (i.e. bulk deposition, which is the sum of wet and dry deposition), because coniferous forests are known to be relatively efficient at intercepting dry deposition. This dry deposition is subsequently washed-off as rainfall passes down through the crown canopy, and the amount of e.g. sulphate in stand throughfall is therefore normally considerably greater than that measured in the open (Lindberg and Lovett 1992). Determining the actual deposition sulphur load on the forest floor therefore means that so-called stand throughfall must also be monitored. There is also a certain amount of interaction between the chemical compounds in deposition and the tree canopies but, in the case of sulphate, this is relatively limited (Lindberg *et al.* 1986, Bredemeier 1988, Draaijers and Erisman 1995).

Deposition loads of a wide range of ions from the atmosphere to the forest floor below the tree canopies (stand throughfall) have been investigated in a number of studies in Finland in order to determine the contribution and effects of these fluxes on the biogeochemical cycling of chemical elements and compounds within forest ecosystems (e.g. Hyvärinen 1990, Ukonmaanaho *et al.* 1998, Lindroos *et al.* 2000, Piirainen *et al.* 2002). Ukonmaanaho *et al.* (1998) and Lindroos *et al.* (2000) reported a decreasing trend in sulphur deposition to the forest floor in stand throughfall during 1989–1997. The proportion of sulphate washed off from the tree canopies (corresponding to dry deposition) has been found to make an important contribution to the total sulphur deposition in stand throughfall in Finnish conditions (Lindroos *et al.* 2000).

Sulphur deposition was as its highest during the 1980s in Finland but, since then, the deposition load has decreased considerably due to reductions in sulphur emissions (Nordlund 2000). Acidifying sulphur compounds are considered to have negative effects on forest health either directly (e.g. sulphur dioxide) or indirectly by increasing soil acidification (e.g. Berdén *et al.* 1987). In Finland, the effects of acidifying deposition on forest health have been investigated in a number of studies since the 1980s, and the defoliation degree of trees has been used to indicate their overall state of health (Strand 1997, Forest condition in Europe 1999, Lindgren *et al.* 2000, Derome *et al.* 2001). In studies carried out in Finland, no direct overall connection has been found between acidifying sulphur deposition and forest health expressed as the degree of defoliation (Lindgren *et al.* 2000, Derome *et al.* 2001). On the Kola Peninsula close to Finland's northeastern border, however, the defoliation degree has been relatively high in areas affected by high sulphur and heavy metal deposition derived from local industrial point sources (Lindroos *et al.* 1995, Salemaa *et al.* 1995). In this area the degree of defoliation is also strongly affected by the direct effect of toxic levels of sulphur dioxide in the atmosphere on tree foliage. Many of these studies have been based on comparison of the defoliation degree and e.g. the sulphur deposition at different monitoring plots. However, relatively little is known about plotwise changes in the deposition load of acidifying compounds and its possible relationship to the defoliation degree.

The first of the two aims of this study was to determine whether the reductions in sulphur emissions, which started during the late 1980s and early 1990s, continue to be reflected in sulphur deposition measured both in the open and inside the stand during the period 1996–2003. The second aim was to estimate the proportion of sulphate deposition washed off from the tree canopies (net-throughfall) out of the total deposition in coniferous stands. We also hypothesized that possible changes in the deposition of acidifying compounds would be better reflected in the plotwise level of forest condition than in between-plot comparisons. This is because, in between-plot comparisons, many factors can vary considerably between the plots and subsequently also have a significant effect on the defoliation degree. We therefore investigated the plotwise relationships between the trends in sulphate deposition in bulk deposition and stand throughfall and the degree of defoliation during the period 1996–2003.

Material and methods

Deposition samples were collected throughout the year and the defoliation degree estimated annually in 8 Norway spruce and 8 Scots pine stands in the Finnish intensive monitoring (Level II) network (*see* Fig. 1 and Table 1) of the EU-Forest Focus/UN-ECE Pan-European Level II Forest Condition Monitoring network (ICP Forests). Thirteen of the monitoring plots were located in commercially exploited forests that were relatively even aged and had a homogeneous forest structure. The remaining three plots (numbers 19, 20 and 21) were located in relatively pristine areas where forestry management had not been carried out for a considerable period of time. The mean age of the tree stands on these three plots was high (Table 1). The Scots pine plots were located on soils composed of sorted sand, and the Norway spruce stands on till soils.

The deposition samples were collected inside the stand (stand throughfall) and in an adjacent open area (bulk deposition) at 4-week intervals during the winter and spring, and at 2-week intervals (bulked to give one sample per 4-week interval) during summer and autumn during the period 1996–2003. The open area was located at about 300 m distance from the tree stand. There were 20 systematically located precipitation collectors (Ø = 20 cm, h = 0.4 m) within the stand during the snow-free period, and 6–10 snow collectors (Ø = 36 cm, h = 1.8 m) during winter. The corresponding number of collectors for the adjacent open area was 3 and 2, respectively. The design of the deposition monitoring plots is given in Raitio *et al.* (2002). The samples were filtered in the laboratory through 0.45 μm membrane filters, and the sulphate (SO_4-S) concentrations determined by ion chromatography (IC). Plot-specific linear regressions were calculated in order to determine whether there were statistically significant temporal trends in sulphate deposition. These regression equations were statistically tested using the F- and t-tests.

The defoliation degree was estimated using 5% classes (0% = 0%, 1%–5% = 5%, 6%–10% = 10%, 11%–15% = 15%, etc.) and expressed as the relative needle loss. The tree to be estimated was compared with a completely non-defoliated tree (an imaginary tree with a defoliation degree of 0%). A defoliation degree of 100% means that the tree has lost all its leaves or needles. The defoliation degree of 25% is generally considered to represent the limit value above which the tree

Table 1. The amount of precipitation and some characteristics of the stands on the monitoring plots. BD = bulk deposition, TF = stand throughfall, SP = Scots pine, NS = Norway spruce.

Monitoring plot	No.[1]	Lat. N	Precipitation (BD) (mm[2])	Precipitation (TF) (mm[2])	Tree species	Stand age[3] (years)	Basal area with bark[3] (m^2 ha^{-1})
Sevettijärvi	1	69°	410 (70)	367 (63)	SP	200	13.4
Kivalo	6	66°	587 (113)	469 (88)	SP	55	21.3
Ylikiiminki	9	64°	551 (93)	467 (81)	SP	90	12.5
Lieksa	20	63°	580 (85)	522 (67)	SP	130	28.8
Juupajoki	10	61°	629 (76)	521 (63)	SP	80	17.9
Punkaharju	16	61°	526 (76)	363 (56)	SP	80	29.4
Tammela	13	60°	619 (97)	471 (77)	SP	60	21.9
Miehikkälä	18	60°	600 (82)	476 (71)	SP	120	16.9
Pallasjärvi	3	67°	545 (81)	458 (62)	NS	140	13.0
Kivalo	5	66°	585 (100)	552 (97)	NS	70	21.6
Oulanka	21	66°	431 (65)	469 (80)	NS	170	25.6
Uusikaarlepyy	23	63°	462 (138)	269 (62)	NS	55	34.8
Juupajoki	11	61°	629 (76)	464 (64)	NS	80	33.2
Punkaharju	17	61°	526 (76)	342 (62)	NS	70	28.5
Evo	19	61°	616 (79)	445 (60)	NS	170	54.1
Tammela	12	60°	584 (82)	430 (54)	NS	60	27.6

[1] Site code. [2] Mean (S.D.), 1996–2003. [3] Raitio *et al.* (2002).

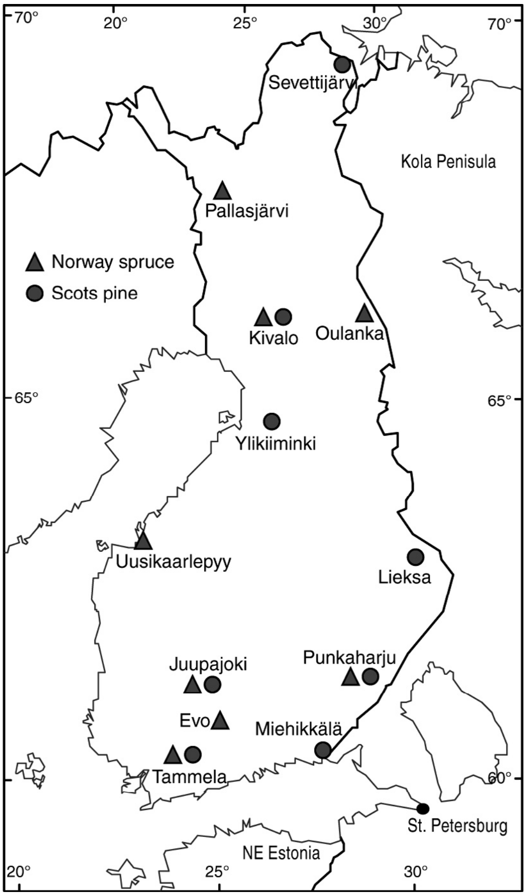

Fig. 1. Map of Finland showing the location of the monitoring plots in the Norway spruce and Scots pine stands.

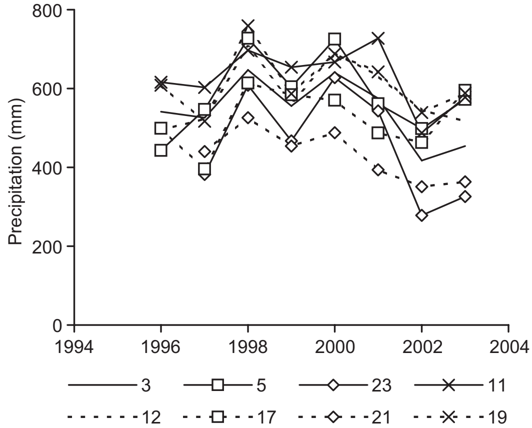

Fig. 2. Annual precipitation in the open area for the Norway spruce stands during 1996–2003. The numbers in the legend refer to the plot number (*see* Fig. 1 and Table 1 for their location).

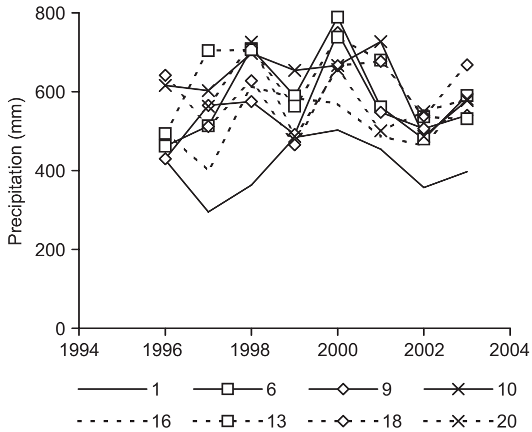

Fig. 3. Annual precipitation in the open area for the Scots pine stands during 1996–2003. The numbers in the legend refer to the plot number (*see* Fig. 1 and Table 1 for their location).

is damaged (Forest condition in Europe 1999). Defoliation was estimated on the upper half of the living crown in the case of Norway spruce and the upper two thirds in the case of Scots pine. The mean defoliation degree for the plot was calculated from 60 trees. Pearson's correlation coefficients were calculated for each of the plots separately in order to study whether there is a relationship between the sulphur deposition values in bulk deposition and stand throughfall and the defoliation degree.

Results

Precipitation

The mean annual precipitation in the open areas varied between 410–629 mm at the different monitoring sites (Table 1). The spruce stand canopies intercepted, on average, 26% of the precipitation measured in the open (excluding the Oulanka plot, no. 21). No interception occurred on the Oulanka plot in NE Finland, and throughfall precipitation was even higher than that in the open area. In the pine stands the interception value was clearly lower (mean 19%) than that in the spruce stands. No clear trends were found for the annual amount of precipitation in the open area and in stand throughfall during the period 1996–2003 (Figs. 2 and 3).

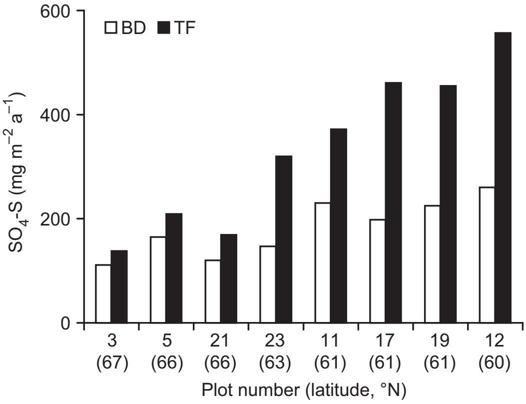

Fig. 4. The mean annual SO_4-S deposition in bulk deposition (BD) and in stand throughfall (TF) during 1996–2003 in 8 Norway spruce stands. The plot number and latitude of the plots is given below the *x*-axis (*see* Fig. 1 and Table 1 for their location).

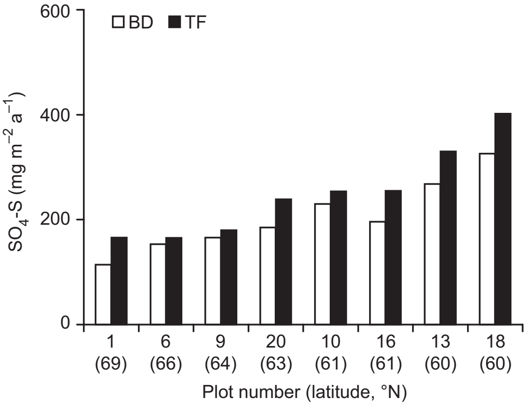

Fig. 5. The mean annual SO_4-S deposition in bulk deposition (BD) and in stand throughfall (TF) during 1996–2003 in 8 Scots pine stands. The plot number and latitude of the plots is given below the *x*-axis (*see* Fig. 1 and Table 1 for their location).

Deposition

Mean sulphate deposition in the open area (BD) varied between 111–326 mg S m^{-2} yr^{-1} during 1996–2003. The deposition values were higher on the plots located in southern Finland than those in the north (Figs. 4 and 5). The highest plotwise mean sulphate deposition in stand throughfall (TF) during 1996–2003 was 557 mg S m^{-2} yr^{-1}, and was measured on the Tammela spruce plot (no. 12) located in southern Finland. The corresponding lowest value was 138 mg S m^{-2} yr^{-1} on the northernmost spruce plot (Pallasjärvi, no. 3). The sulphate deposition values in stand throughfall were also generally higher in southern Finland than in the northern part of the country (Figs. 4 and 5).

The spruce canopies clearly caused a stronger increase in the sulphate flux on the forest floor than the pine canopies, and net-throughfall of sulphate (i.e. TF–BD, sulphate wash-off) from the canopy was higher in the southern parts of the country than in northern Finland (Figs. 4 and 5). The net-throughfall of sulphate varied between 141 ± 86–296 ± 117 mg S m^{-2} yr^{-1} (mean ± S.D.) on the spruce plots in southern and central Finland, while the corresponding range for the plots in northern Finland was 27 ± 11–49 ± 18 mg S m^{-2} yr^{-1}. The relative increase in sulphate deposition as precipitation passed down through the canopy layer on the spruce plots was, on average, 36%–56% in southern and central Finland, and 19%–29% in northern Finland. The corresponding values (i.e. TF–BD) for the pine stands in southern and central Finland were 24 ± 18–76 ± 32 mg S m^{-2} yr^{-1} (9%–22%), and in northern Finland 14 ± 20–15 ± 13 mg S m^{-2} yr^{-1} (8%). The Sevettijärvi plot (no. 1) located in the NE corner of northern Finland has been excluded from these ranges for the pine stands because the values measured on this plot clearly differed from the general pattern of net throughfall of sulphate. The mean net-throughfall of sulphate for the monitoring period on this plot was 52 ± 18 mg S m^{-2} yr^{-1}, and the proportion of sulphate deposition washed-off from the canopy was 31% despite the fact that this plot is the northernmost plot in the whole monitoring network.

Trends in sulphate deposition

Sulphate deposition in the open area and in stand throughfall during 1996–2003 on many of the spruce and pine plots located in southern Finland showed a significant or almost significant decrease over time. This was reflected in the linear regressions ($p < 0.05$ or < 0.10) (Table 2 and Figs. 6 and 7). On the two pine plots in SE Finland (nos. 16 and 18), there was no signifi-

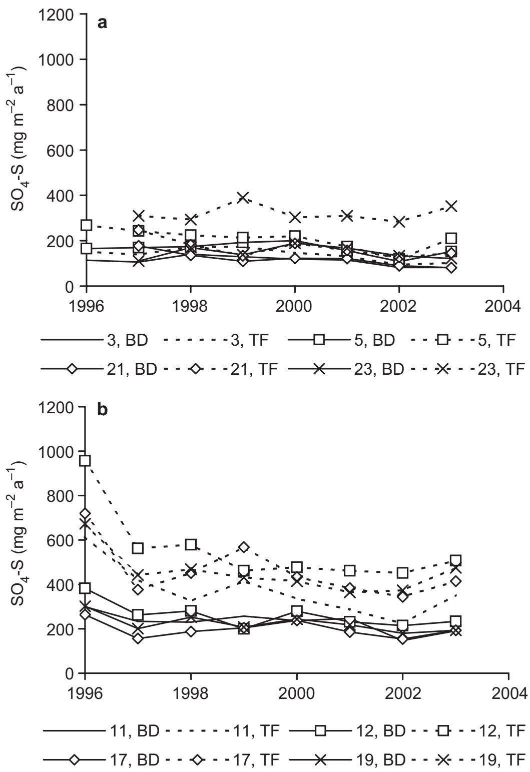

Fig. 6. Trends in SO_4-S deposition in bulk deposition (BD) and in stand throughfall (TF) during 1996–2003 in 8 Norway spruce stands in (**a**) northern and (**b**) southern Finland. The numbers in the legend refer to the plot number (*see* Fig. 1 and Table 1 for their location).

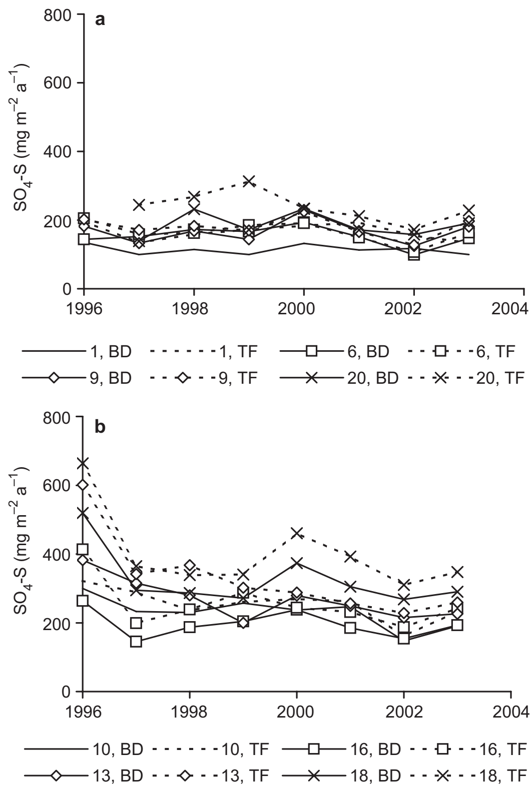

Fig. 7. Trends in SO_4-S deposition in bulk deposition (BD) and in stand throughfall (TF) during 1996–2003 in 8 Scots pine stands in (**a**) northern and (**b**) southern Finland. The numbers in the legend refer to the plot number (*see* Fig. 1 and Table 1 for their location).

Table 2. Linear regression equations for the SO_4-S deposition (mg m^{-2} a^{-1}) and time (years 1996–2003). Deposition = intercept + X variable × year. BD = bulk deposition, TF = stand throughfall, NS = Norway spruce, SP = Scots pine, Lat. = latitude. Only statistically significant equations are presented.

Tree species	Plot	Lat.	Type	R^2	Intercept (S.E.)	*p*	X variable (S.E.)	*p*	*n*
NS	3	67	TF	0.52	17175.9 (6672.2)	0.042	–8.52 (3.34)	0.043	8
	5	66	TF	0.57	28033.1 (9916.6)	0.030	–13.92 (4.96)	0.031	8
	21	66	BD	0.80	26405.3 (5901.9)	0.007	–13.14 (2.95)	0.007	7
	21	66	TF	0.52	27883.0 (11888.6)	0.066	–13.86 (5.94)	0.067	7
	11	61	BD	0.56	27878.5 (10043.8)	0.032	–13.83 (5.02)	0.033	8
	11	61	TF	0.56	72253.3 (25817.6)	0.031	–35.95 (12.91)	0.032	8
	17	61	TF	0.38	63376.5 (32603.8)	0.100	–31.47 (16.31)	0.102	8
	19	61	BD	0.47	22528.8 (9601.6)	0.057	–11.15 (4.80)	0.059	8
	19	61	TF	0.39	49490.4 (25274.5)	0.098	–24.52 (12.64)	0.100	8
	12	60	BD	0.47	32369.6 (13824.9)	0.058	–16.06 (6.91)	0.059	8
	12	60	TF	0.49	96620.6 (40057.9)	0.052	–48.04 (20.03)	0.053	8
SP	10	61	BD	0.56	27890.0 (10035.8)	0.032	–13.83 (5.02)	0.033	8
	10	61	TF	0.53	28270.9 (10802.1)	0.040	–14.01 (5.40)	0.041	8
	13	60	BD	0.61	38496.8 (12389.2)	0.021	–19.12 (6.20)	0.022	8
	13	60	TF	0.66	79144.0 (22939.2)	0.014	–39.42 (11.47)	0.014	8

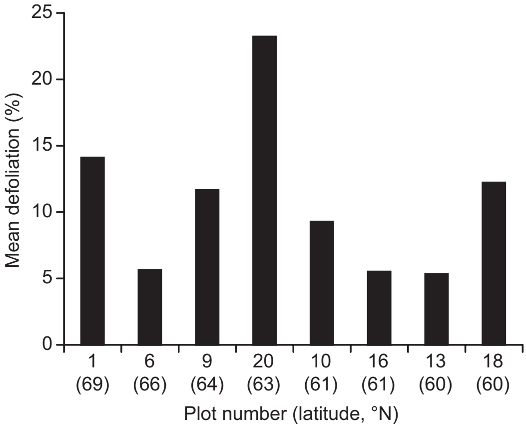

Fig. 8. Mean defoliation degree of the Scots pine stands in 1996–2003. The plot number and latitude of the plots is given below the *x*-axis (*see* Fig. 1 and Table 1 for their location).

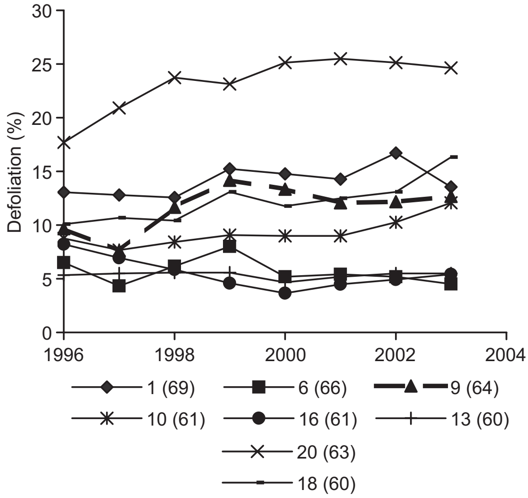

Fig. 9. Annual defoliation degree of the Scots pine stands during 1996–2003. The numbers in the legend refer to the plot number and latitude (in parentheses) (*see* Fig. 1 and Table 1 for their location).

cant decrease during the monitoring period even though the highest sulphate deposition values were recorded in 1996 (Fig. 7).

No decreasing trends during the monitoring period were found for sulphate deposition in the open area and in stand throughfall in the pine stands located in northern Finland (Fig. 7). The trend was statistically significant for some of the spruce stands in northern Finland, but the decrease in sulphate deposition was limited by the fact that the deposition level in 1996 was already very low (Fig. 6).

Defoliation degree

The mean defoliation degree of the Scots pine stands varied by 5%–23% during the period 1996–2003 (Fig. 8). There was no clear geographical trend in the defoliation values, and the highest mean value was determined on the plot in eastern Finland (Lieksa, no. 20). The age of the trees on this plot is relatively high (mean 130 yrs) and the plot is located in an area where forestry practises have not been carried out for many decades. The yearly mean defoliation values were relatively stable for most of the pine stands during the period 1996–2003 (Fig. 9). The only clear change (i.e. increase) in the defoliation degree during the study period was detected on the Lieksa plot (no. 20). No statistically significant ($p < 0.05$) correlations were found between the defoliation degree and sulphate deposition in bulk deposition or in stand throughfall on any of the pine sites (Table 3).

The mean defoliation degree of the Norway spruce stands varied by 9%–28% during the period 1996–2003 (Fig. 10). The highest mean

Table 3. Correlations between SO_4-S deposition in bulk deposition (BD) and stand throughfall (TF) and defoliation degree (DEF, %) in Norway spruce (NS) and Scots pine (SP) stands. Statistically significant correlations ($p < 0.05$) are set in boldface.

Tree species	Plot	BD	TF	*n*
NS	3, DEF	–0.58	**–0.71**	8
	5, DEF	–0.07	–0.60	8
	21, DEF	0.04	–0.14	7
	23, DEF	–0.38	0.23	7
	11, DEF	**–0.83**	–0.71	8
	12, DEF	–0.60	–0.59	8
	17, DEF	0.43	0.22	8
	19, DEF	**–0.72**	**–0.79**	8
SP	1, DEF	0.05	0.13	8
	6, DEF	0.22	0.42	8
	9, DEF	0.30	0.07	8
	20, DEF	0.42	–0.51	7
	10, DEF	–0.57	–0.53	8
	16, DEF	0.14	0.55	8
	13, DEF	–0.21	0.06	8
	18, DEF	–0.47	–0.47	8

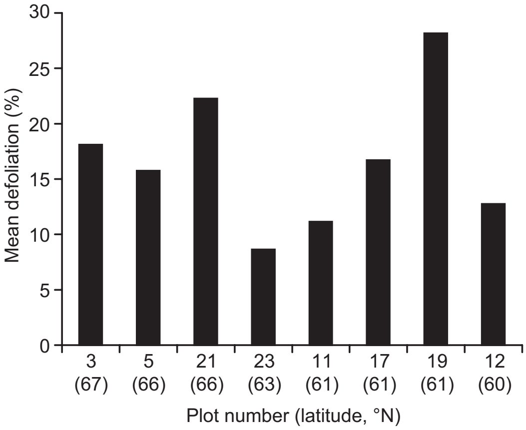

Fig. 10. Mean defoliation degree of the Norway spruce stands in 1996–2003. The plot number and latitude of the plots is given below the *x*-axis (*see* Fig. 1 and Table 1 for their location).

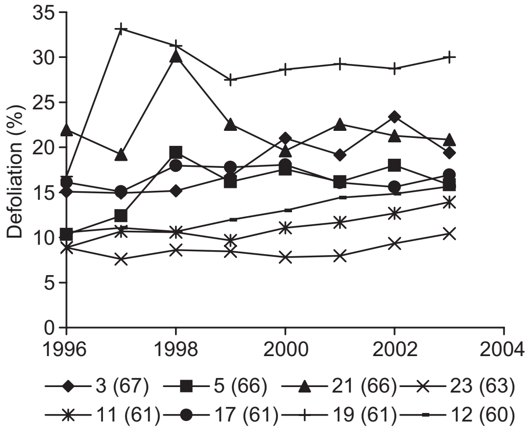

Fig. 11. Annual defoliation degree of the Norway spruce stands during 1996–2003. The numbers in the legend refer to the plot number and latitude (in parentheses) (*see* Fig. 1 and Table 1 for their location).

value was determined on the Evo plot (no. 19) in southern Finland. The stand age is relatively high on this plot (mean 170 years), and the plot is located in a pristine area with no forestry management for a long period of time. The clearest change in the yearly mean defoliation degree during the study period was detected on this plot, where the defoliation value increased sharply between the years 1996 and 1997 (Fig. 11). For some of the Norway spruce stands there was a slight increase in the defoliation degree during 1996–2003, although the absolute change was very small. In general, the values remained very stable during the study period. No significant ($p < 0.05$) positive correlations were found between the sulphate deposition in bulk deposition and stand throughfall and the degree of defoliation; i.e. although sulphate deposition showed a decreasing trend during 1996–2003 on some of the plots, this was not associated with any decreasing trend in defoliation on any of the plots (Table 3). In fact, an opposite trend was found in some of the spruce stands (nos. 3, 11, 19).

Discussion

Precipitation

Although stand structure usually has an effect on the amount of precipitation reaching the forest floor in stand throughfall, the most important factor in Finnish conditions is the amount of precipitation falling in the open (Starr 1995, Lindroos *et al*. 2000). This was clearly evident from the statistically significant correlations ($p < 0.05$) between the amount of precipitation in the open (bulk deposition) and in stand throughfall (pine stands: $r = 0.81$, spruce stands: $r = 0.78$). However, the situation at one of the spruce plots (Oulanka, no. 21) was different to that at the other plots. On this plot the amount of stand throughfall is high presumably because of the windy conditions during wintertime: large amounts of snow accumulate in the tree canopies, but considerably less on the ground in the open area. The interception of precipitation as it passes down through the canopy layer was lower in the pine stands than in the spruce stands due to the differences in crown structure between the two tree species (Hyvärinen 1990). The mean proportion of precipitation retained by the canopies (pine 19%, spruce 26%) was very close to the values reported by Lindroos *et al*. (2000) for a different monitoring network in Finland, in operation at the beginning of the 1990s, where most of the 43 monitoring plots were located in eastern and northern Finland.

Deposition

Sulphate deposition is generally higher inside the stand than in the open due to the wash-off of dry deposition accumulated in the tree canopies (Lindberg and Lovett 1992). As a result, sulphate deposition in stand throughfall is generally considered to represent rather well total sulphate deposition from the atmosphere into the forests (ICP Forests Manual 1998). The sulphate deposition values measured in this study in the open areas, as well as inside the stands, were very low compared to the deposition situation in the southern parts of Scandinavia and central Europe (De Vries *et al*. 2001). Higher sulphur deposition in southern Finland than in the northern parts of the country has also earlier been reported in many other studies (e.g. Järvinen and Vänni 1990, Ruoho-Airola *et al*. 1998, Ukonmaanaho *et al*. 1998, Nordlund 2000). There was a clear decreasing gradient in sulphate deposition from south to north throughout Finland in both the open and in stand throughfall.

Sulphate deposition in stand throughfall was higher in the spruce stands than in the pine stands although deposition in the open was at a similar level. This is undoubtedly due to differences in the canopy structure of the two tree species. Norway spruce canopies intercept dry deposition from the atmosphere more effectively than pine canopies (Bredemeier 1988). There was a clear decreasing gradient running from southern to northern Finland in net-throughfall of sulphate in both the spruce and pine stands. However, net-throughfall of sulphate varied considerably between the stands. The highest sulphate net-throughfall values were over 50% of stand throughfall deposition, while the lowest values were less than 10%. The proportion of net-throughfall of sulphate out of the total sulphate load to the forest floor has obviously been considerable on many of the plots during the study period, which means that even though the general deposition load has clearly decreased during the last decades and years, the net-throughfall of sulphate still makes an important contribution to the total deposition load on the forests and forest floor in Finnish conditions. However, an interesting result was also the fact that, on some of the plots, the difference between the annual sulphate deposition in stand throughfall and bulk deposition in the open was very small, i.e. the proportion of net-throughfall of sulphate was almost insignificant.

The situation on the northernmost plot (Sevettijärvi pine plot, no. 1) differed from that at the other plots in that there was no decreasing gradient in net-throughfall of sulphate. On this plot, 31% of the sulphate deposition in stand throughfall was derived from wash-off from the canopy layer. This value is high compared to that at the other plots in northern Finland. However, the plot is located only 70 km to the west from the major sulphur emission sources on the Kola Peninsula (Cu-Ni smelters), NW Russia, as well as being located close to the Barents Sea (part of the Arctic Ocean) and therefore receives sulphate from marine sources. Both of these factors undoubtedly considerably increase the dry deposition of sulphate, and subsequently sulphate wash-off from the canopy layer. It has been estimated that marine-derived sulphate (SO_4-S) accounts for about 10% of the total sulphate deposition in BD and 13% in TF on this plot (no. 1) (Lindroos *et al*. 2001). The effect of emissions from the smelters is reflected in somewhat elevated heavy metal concentrations in pine needles on this plot (Raitio 1999). The overall impact of sulphur and heavy metal emissions on forest ecosystems in Finnish Lapland has been found to be relatively limited (Tikkanen and Niemelä 1995).

Time trends in sulphate deposition

Sulphur deposition in Finland has decreased since the beginning of the 1980s (Nordlund 2000). A similar decrease in the amounts and concentrations of sulphate deposition in stand throughfall has also been reported during the period 1989–1997 (amounts) and 1989–1995 (concentrations) on sites belonging to the ICP/Integrated Monitoring network in Finland (Ukonmaanaho *et al*. 1998, Lindroos *et al*. 2000). Three of these plots are now part of the ICP Forests monitoring network and were included in our study. During the 1996–2003 monitoring period, sulphate deposition in the open and in stand throughfall continued to decrease linearly on many of the plots located in southern Finland, despite the fact that the deposition values were already much lower in 1996 than earlier. The decreasing trend was evident on both the pine and spruce plots. Because there was no corresponding decrease in the amount of precipitation during the same period, the reason for the decrease in sulphate deposition in the open and in stand throughfall on these plots was the decrease in the sulphate concentrations. On two pine sites in south-eastern Finland, however, sulphate deposition in the open and in stand throughfall did not decrease linearly. The values were higher in 1996 than in any of the other years, but there was otherwise no clear decreasing trend. Deposition in this part of the country is considerably influenced by emission sources in the St. Petersburg area and the shale-oil power stations located in NE Estonia.

There were no decreasing trends for sulphate deposition in the open and in stand throughfall on the pine plots in northern Finland. Although a decreasing trend was found for some of the spruce sites in northern Finland, the absolute deposition levels decreased only slightly because the deposition levels in northern Finland have earlier been already very low. Overall, it is clear that the reductions in sulphur dioxide emissions are reflected as lower deposition values in many parts of Finland, and the deposition levels are currently relatively low.

Defoliation degree

The mean defoliation degree was generally very low on the plots; < 15% for the Scots pine stands and < 20% for the Norway spruce stands. The only exception to these values for the Scots pine stands was the Lieksa plot (no. 20) located in eastern Finland, where the mean defoliation was 23%. For the Norway spruce stands, the exceptions were the Oulanka plot (no. 21) and the Evo plot (no. 19) with values close to or above 25%. On all these plots, the stand age is relatively high and no forestry management has been performed for many decades, i.e. the plots are located in semi-natural, relatively pristine forest. Stand age is known to be an important natural factor causing defoliation (Lindgren *et al*. 2000), and this was also clearly reflected in our study. The annual defoliation values were stable or indicated a slight increase in defoliation on many of the plots during 1996–2003. However, the changes were in many cases very limited in absolute values. No clear decrease was observed in defoliation on any of the plots during the study period, although there were statistically significant decreasing trends in sulphate deposition values during 1996–2003. This clearly demonstrates that sulphate deposition alone is not, at current levels in Finland, likely to cause changes in forest health in terms of defoliation in the short term at least. Earlier studies also support the conclusion that there is currently no direct connection between the defoliation degree and sulphur deposition in Finland (Lindgren *et al*. 2000, Derome *et al*. 2001).

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