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THROUGHFALL MONITORING AS A MEANS OF MONITORING DEPOSITION TO FOREST ECOSYSTEMS

Evaluation of European data

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SUMMARY

Throughfall monitoring results from Scandinavia and other parts of Europe has been evaluated for its use in estimation of atmospheric deposition to forest ecosystems. The general conclusion is that the method is useful tool in estimating deposition to forests and for producing information about the status of the forest. It can be used separately or in combination with deposition models. For aerodynamically complex terrain such as forest edges throughfall monitoring is the only realistic alternative to estimate sulphur deposition.

The method was found useful for elements for which the interaction with vegetation is small compared to the throughfall fluxes. This is the case for sulphur in most parts, except maybe in remote areas such as the northern Scandinavia. The method cannot be used directly for estimating the deposition of nitrogen to forests due to interaction with the canopy, with the exception of areas with an extremely high nitrogen deposition such as in parts of the Netherlands and maybe during wintertime when the biologic activity is low. The throughfall results for nitrate and ammonium will however provide useful information on the nitrogen load in the forest. Throughfall data for sulphur and ammonium in areas close to ammonia emission sources indicate a co-deposition of ammonia and sulphur dioxide. As for nitrogen, base cation deposition cannot be estimated from throughfall data, due to the internal cycling of these ions.

There are large variations in throughfall fluxes between different forests, due to factor such as forest structure and exposure of the site. Spruce and fir trees have a large filtering capacity, larger than pine and deciduous trees.

THROUGHFALL MONITORING AS A MEANS OF MONITORING DEPOSITION TO FOREST ECOSYSTEMS - EVALUATION OF EUROPEAN DATA

1. INTRODUCTION

At an international meeting in Skokloster in March 1988, critical loads of sulphur and nitrogen were defined for different kinds of ecosystems (Nilsson & Grennfelt, eds. 1988). The critical loads were defined in order to avoid harmful effects on the structure and function of the ecosystem. The sensitivity of one ecosystem is different to another. The critical load of sulphur to avoid acidification depends mainly on the chemical weathering ability of the soil which in turn depends on soil composition and texture. Critical loads for nitrogen can be defined to avoid ecosystem disturbances due to eutrophication as well as to avoid nitrate leakage (N-saturation) and acidification. Important factors are the initial nutrient status of the ecosystem and its ability to take up nitrogen.

Based on the critical load concept, ECE decided to map the sensitivity of European ecosystems in order to point out the areas in which the critical loads are exceeded. As a future consequence this might form a basis for optimizing control strategies.

Besides the mapping of sensitivity, the deposition load must be determined. Even on a local scale, variations in sensitivity as well as in deposition can be considerable. To make proper judgements the local critical loads should be considered in view of the local deposition.

At present deposition data are available mainly as monitoring data from the EMEP¹) or the EACN²) networks. These provide data on the wet part of the deposition and on air pollution concentrations.

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¹) European Monitoring and Evaluation Programme

²) European Air Chemistry Network

The wet deposition measured as bulk precipitation will only represent the total deposition at smooth open field conditions where dry deposition is of minor importance.

Deposition to forests and other types of vegetation for which the dry deposition processes are important, is usually calculated based on air pollution concentrations and theoretical models.

The reason for this is the lack of practical routine procedures to measure the dry deposition part and thus the total deposition. The methods used up to now for monitoring dry deposition, the eddy correlation and the gradient methods, require sophisticated equipment and extensive monitoring efforts.

Theoretically calculated data are, however, not sufficient to describe the total (dry and wet) deposition level and its variations. The EMEP-model, for example, calculates the deposition of sulphur and nitrogen over Europe as a mean value over 150x150 km^2 grid squares. Within these squares, there are large local variations. Monitoring of throughfall has been found to measure the total deposition to forest ecosystems of some pollutants both in Europe and in the U.S. (see below).

2. OBJECTIVE

At the Workshop on mapping, the second preparatory meeting held in Vienna in April 1989, it was decided that, in addition to the manuals for mapping critical loads and levels, a special manual should be prepared for mapping the deposition.

In planning the work of preparing the manual the following suggestions were made:

- For mapping the deposition over Europe, actual monitoring data are necessary. A "standardized" network of throughfall monitoring stations in coniferous forest stands is proposed. However, it will take at least one or two years to have a network in operation, producing data.

- Until then, presently available data must as far as possible be extrapolated to produce information on "vegetation induced" deposition.

The objective of our study is to evaluate the available data to see what are the relations between vegetation structure, air pollution and deposition, and how the data can be used for mapping.

Primarily the deposition of sulphur and nitrogen are of interest. Data on chloride and sodium is needed to exclude the seasalt contribution. Further, data on base cations deposition is of importance as this will give an additional source of buffering when acidification is concerned.

3. FACTORS INFLUENCING THE AERODYNAMIC STRUCTURE OF THE SITE AND THE FILTERING CAPACITY OF THE FOREST STAND

Except for the air pollution load, there are two main factors which will determine the amount of dry deposition. One is the aerodynamic character of the monitoring site and its surroundings The other is the filtering capacity of the recipient.

In order to make dry deposition measurements comparable with data from other sites, it is important to describe and quantify (as far as possible) these parameters which influence the dry deposition process.

The aerodynamic structure of the site can be described by surface roughness, that is, the effect of vegetation on wind movements. High vegetation (forests) or large height differences in vegetation will induce more turbulence than short vegetation (grass). These movements will also be influenced by the topography of the site and surroundings. A forest on a slope directed towards the dominant wind direction will be more exposed to air pollution than a slope facing the opposite direction or a forest on flat land. Hilly as well as patchy terrain with open land mixed with forests and forest edges will induce more turbulence. These conditions should be described as far as possible, e.g. by aerodynamic classes (Davenport 1960). The aerodynamic structure of the surroundings should be given in different wind directions.

The other main factor influencing the dry deposition is the filtering capacity of the "obstacle" e.g. the forest. A tree with leaves will have a larger surface than a tree without any leaves and is expected to be a more efficient filter. The structure of the tree or forest stand must be described if the monitoring results are to be extrapolated for conclusions over larger areas. A number of parameters have been used, alone or in combination:

- tree species
- height of tree (m)
- crown projection (radius of crown, m)
- crown density (density classes)
- stem diameter (m)
- stem density (number of trunks, ha^{-1})
- biomass (m^3)
- leaf area index ($m^2 \cdot m^{-2}$)
- canopy coverage ($m^2 \cdot ha^{-1}$)

4. THROUGHFALL MONITORING AS A MEANS OF MONITORING TOTAL DEPOSITION

The solute flux in stand precipitation consists of wet deposition and dry (including occult) deposition onto the forest canopy and is modified by canopy interaction processes (absorption or leaching), (Parker, 1983). In the following three sections it will be discussed to what extent the stand precipitation data can be used to estimate the atmospheric deposition.

4.1 Sulphur

In several studies the throughfall method has been found to give good estimates of the total deposition of sulphur. For example, in the Gårdsjö study (Hultberg, 1985) throughfall deposition was in agreement with sulphur output from the catchment as well as model calculations.

Table 1. Estimation of the total deposition compared to throughfall and output from a catchment in the Gårdsjö study (Hultberg, 1985).

Table 1. Estimation of the total deposition compared to throughfall and output from a catchment in the Gårdsjö study (Hultberg, 1985).

	Element (kg $ha^{-1}yr^{-1}$)								
	H^+	Ca	Mg	K	Na	NH_4-N	Cl	SO_4-S	NO_3-N
Estimated total deposition (average of 2 hydrological years)	1.02*)	3.8-8.8	5.4-6.1	2.3-6.4	42.9	7.7-11.8	78.5	24.8-31.1	8.6-10.8
Throughfall (only hydrological year 80/81)	0.78(76%)	10.2	6.6	12.9	42.9	4.7	81.6	25.1	5.7
Output from F1 (average of 2 hydrological years)	0.45(44%)	8.8	10.3	4.8	48.4	0.023	78.5	28.8	0.24

*) Calculated from pH in precipitation and H^+ corresponding to SO_2-uptake in vegetation.

Garten et al. (1988) conducted radioactive ^{35}S studies in red maple and yellow poplar trees, to evaluate the applicability of the throughfall method to estimate the atmospheric sulphur deposition. During a 104 days period in the growing season, internal cycling was 0.054 and 0.04 gSm^{-2} for maple and poplar, respectively, being about 7% of the total sulphur deposition in this period. The poplar stand showed relative high internal cycling amounts during the leaf-fall period (0.15 gSm^{-2}), while the maple stand did not show increased internal cycling in this period.

From comparison of these experiments with deposition estimates from air concentration measurements, it was concluded that the throughfall method measures both gaseous and aerosol sulphur deposition and that internal cycling is a minor contributor to the sulphur flux to the forest floor in heavily sulphur polluted areas (Garten et al., 1988). Meiwes and Khanna (1983) estimated leaching from leaf tissues in a sulphur polluted area in Central Europe, by comparing the sulphur concentration of freshly fallen leaf litter with fresh tissue. Their calculations suggest that 0.22 gSm^{-2} could be leached out from senescent leaves of beech and 0.18 gSm^{-2} from senescent spruce leaves. Lindberg et al. (1986) sampled dry deposition on leaves and plates, incident precipitation, throughfall plus stemflow and the concentration of airborne particles and vapors in a mixed hardwood forest in a moderately polluted area in the U.S.A. From these measurements the annual internal sulphur cycling of in this forest was estimated to be 0.09 $gSm^{-2}yr^{-1}$. Lindberg et al. (1986) concluded that sulphur was not retained by the foliage and that SO_2 adsorbed by the leaves will be leached by subsequent rain events. Fassbender (1977) conducted canopy leaching experiments on young spruces exposed to clean air and did not find significant foliar leaching of sulphur.

Combining these findings it can be assumed that internal sulphur cycling in forests in general will be less than 0.2 $g\ m^{2}yr^{-1}$. Therefore it can be concluded that sulphur fluxes in throughfall in central and western Europe are mainly caused by a very efficient filtering of air pollutants by the forest and that these fluxes only marginally are influenced by canopy exchange. In remote areas the throughfall fluxes are only slightly higher than bulk precipitation fluxes. At such locations dry deposition to forests is a minor contributor to total atmospheric deposition and internal cycling of sulphur might be a significant contributor (up to 20%) to the throughfall.

4.2 Nitrogen

Lovett et al. (1985) reported retention of inorganic nitrogen of 0.27 to 0.46 $gm^{-2}yr^{-1}$ by deciduous forest canopies. Indications for canopy retention of NO_3-N and NH_4-N were also found by Hultberg (1983) and Hasselrot & Grennfelt (1987). Roelofs et al. (1985) showed that pine needles can take up NH_4 from an ammonium solution. Retention of nitrogen can be illustrated by the measurements of the southern Swedish monitoring network.

Conversely, nitrogen also can be leached out of the canopy, mainly as organic nitrogen (Carlisle et al., 1966; Alenäs & Skärby, 1988; Fassbender, 1977). Fluxes of organic nitrogen in throughfall are measured only occasionally. It was not possible to draw conclusions on the organic nitrogen flux in throughfall based on the data sets in the present study.

It can be concluded that the inorganic nitrogen flux in throughfall to some extent will be an underestimate of the atmospheric deposition.

In heavily polluted areas, such as The Netherlands, the nitrogen deposition is so large that the uptake is comparably small. In such areas, throughfall can be used to quantify the total deposition.

4.3 Basic cations

To calculate soil acidification rates, the amount of (non sea-salt) basic cations brought into the forested ecosystem by atmospheric deposition has to be known. The atmospheric input of basic salts like carbonates will counteract the soil acidification, by replenishing the basic cations leached out of the soil. The basic cations of interest are calcium, magnesium and potassium. It is not possible to derive the atmospheric deposition to forests directly from the bulk precipitation flux or the throughfall flux. The bulk precipitation flux will underestimate the deposition to the forest, because it neglects the filtering of particles by the forest. This filtering effect should be taken into account in the estimation of basic cation deposition.

A substantial part of calcium, magnesium and potassium in throughfall can be caused by internal cycling of these elements (Bredermeier, 1988; Parker, 1983). In contrary, also irreversible uptake of calcium and magnesium have been found (Alcock and Morton, 1981; Abrahamson et al., 1976; White and Turner, 1970). Therefore throughfall fluxes either can be overestimates or underestimates of atmospheric base cation deposition.

To determine the magnitude of the atmospheric deposition of base cations to forests, three approaches have been used (Ivens, 1989b), (Table 2).

Table 2. Three options to calculate deposition of non sea-salt calcium, magnesium and potassium to forest from bulk precipitation and throughfall measurements.

approach	formula
bulk precipitation	DEPx = BPx
throughfall	DEPx = TFx
filtering	DEPx = BPx * TF_{Na}/BP_{Na}

DEPx = calculated atmospheric deposition of cation x to forest;

BPx,TFx = respectively bulk precipitation and throughfall flux of cation x;

BP_{Na}, TF_{N} = respectively bulk precipitation and throughfall flux of sodium.

The bulk precipitation approach yields a minimum estimate of the atmospheric deposition to the forest. The throughfall deposition gives the actual input of base cations to the forest soil, but does not give a clear insight of the alkaline atmospheric input to the forest ecosystem.

The filtering approach only yields useful results, when calcium/ magnesium/potassium-bearing particles are in the same size range as sodium-bearing particles. Not much detailed information of the size range of these substances is available in literature, but in general it is assumed that all these substances belong to the same group of relative large atmospheric particles. Using present day knowledge, the filtering approach is the best estimate for atmospheric deposition of basic cations. The other two approaches show the limits of uncertainty.

5. VARIABILITY IN THROUGHFALL DATA DUE TO THE FOREST EDGE EFFECT

In addition to the variability of deposition in forests with regard to forest structure there is an effect of increased deposition at the forest edges.

Deposition of air pollutants to forests are usually thought of as a vertical flow from the atmosphere to the forest surface. A European forest is however to a large extent inhomogeneous with many edges facing clear cuttings, lakes, open fields etc., which will make also the horizontal flow of pollutants important.

Throughfall monitoring in Sweden, Denmark and The Netherlands (Hasselrot & Grennfelt, 1987; Grennfelt & Hasselrot, 1987; Beier & Gundersen (1989); Ivens et al., 1988; Draaijers et al., 1988) have shown the deposition pattern at forest edges. The results have also pointed out the necessity to be aware of those variabilities when quantifying the deposition for assessment of effects.
The forest edge will disturb the vertical wind profile and induce air turbulence which will increase the dry deposition. The trees at the edge will in this way collect more pollutants than will the trees in the middle of the stand. This decrease of deposition from the front into the forest has been found to be exponential (Beier & Gundersen, 1989).

The deposition at the front is considerably higher compared to that in the open field and also to that within the forest. In all the studies this edge effect is observed but there is a difference in its magnitude.

In Denmark (Norway spruce) the deposition at the front (figure 1) is higher by a factor of 10-20 compared to the bulk precipitation For most ions the increase is a factor 10. For sea salt particles (Na^+ and Cl^-) the factor is nearly 20. Compared to deposition in the forest, the deposition to the edge is a factor 2-4 higher for most of the ions.

The Swedish results (pine) indicate that the deposition at the front is a factor 5-10 higher than the bulk precipitation (figure 2). Also the Swedish measurements showed a maximum effect for sea salt partices, (factor of 10). The forest edge deposition is, higher by a factor of 2-3 than that inside the forest.

In the Dutch study (Douglas fir) the samplers nearest the front were placed 10 m into the forest (figure 3). At this distance there was an increase for most ions by a factor of 3-10 in relation to open field deposition. A factor of near 20 was seen for sodium (sea salt). In relation to the deposition in the forest, the deposition at 10 m distance from the edge is 20-100% higher for sulphate and ammonium and a factor of 2-3 higher for sodium.

These differences in the forest edge effect are most probably due to differences in the edge and forest structure. One obvious difference is that different tree species were studied; spruce, pine and Douglas fir. There are also other factors beside the density of the stands, such as differences in edge direction and air pollution load which will affect the results.

It is not clear today how much a "normally patchy" landscape will affect the deposition level on a large scale. Locally, however it is obvious that the increased deposition may have a local effect on the vitality of the trees at the edge.

Figure 1. Results from the Danish forest edge study (Beier & Gundersen 1989)

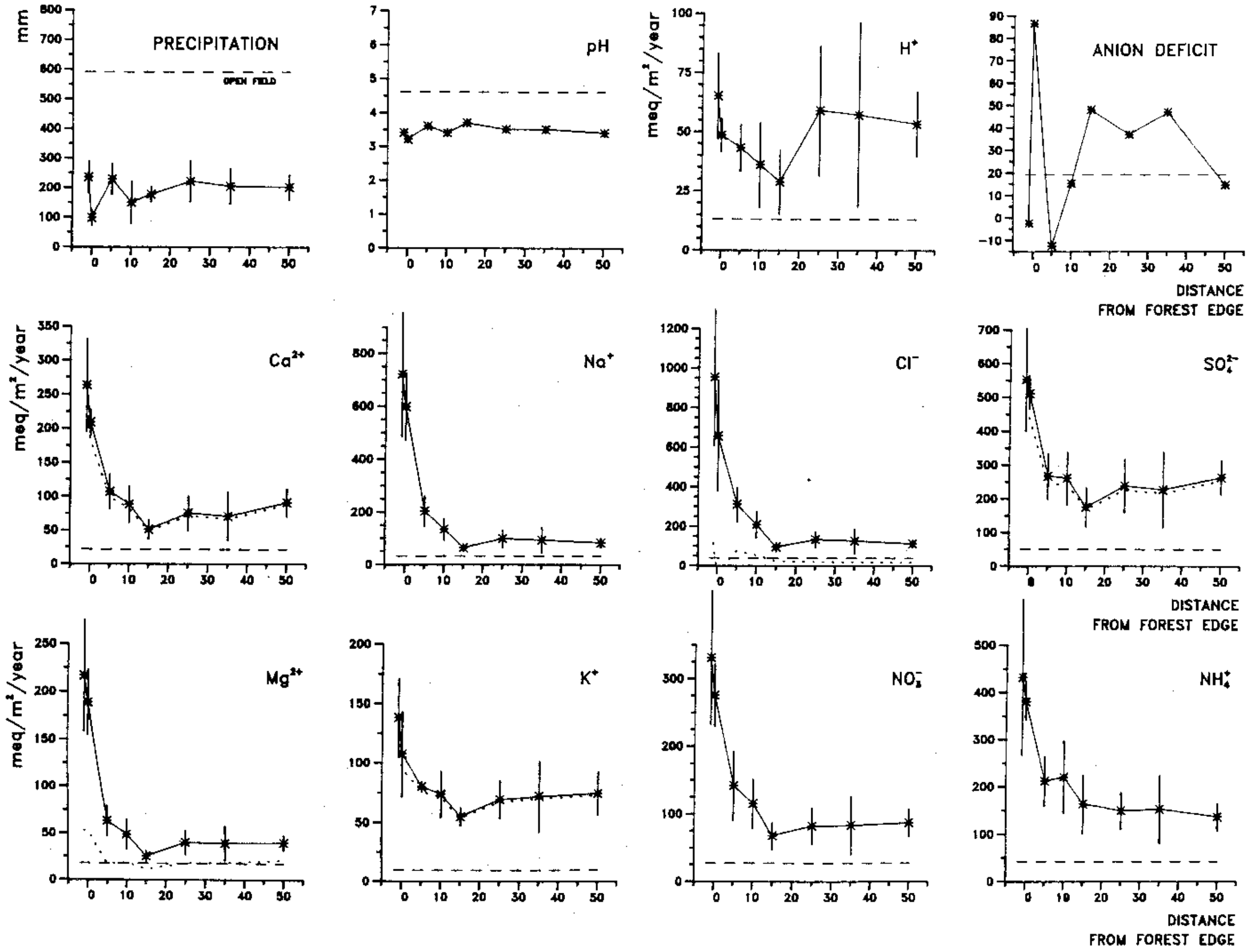


Figure 2 a). Results from the Swedish forest edge study, (Hasselrot & Grennfelt, 1987).

Throughfall deposition to forest floor of sulphate (excess), nitrate, ammonia, and water in a wind-exposed forest edge in southwestern Sweden. The horizontal line represents open-field sampling (bulk deposition). Samples were taken from June 27 to December 12, 1983.

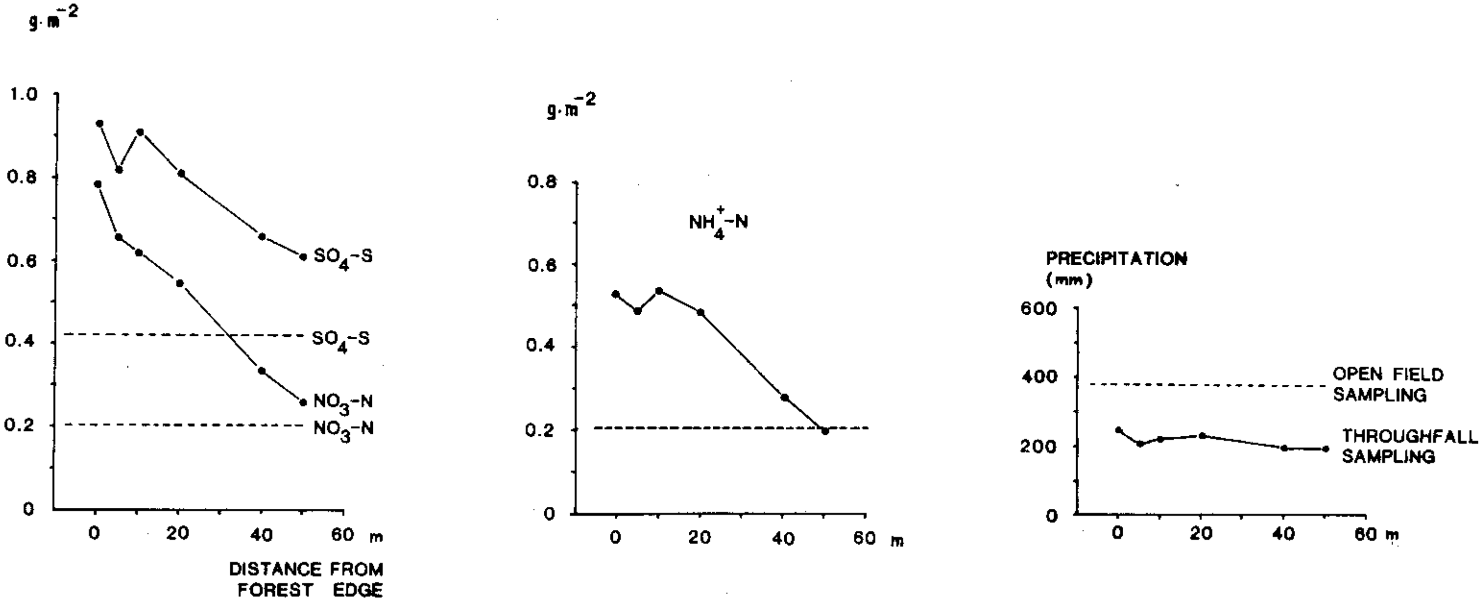


Figure 2 b). Results from the Swedish forest edge study, (Hasselrot & Grennfelt, 1987).

Throughfall deposition to forest floor of hydrogen, sodium and chloride in a wind-exposed pine forest edge in southwestern Sweden. The horizontal line represents open-field sampling (bulk deposition). Samples were taken from June 27 to December 12, 1983.

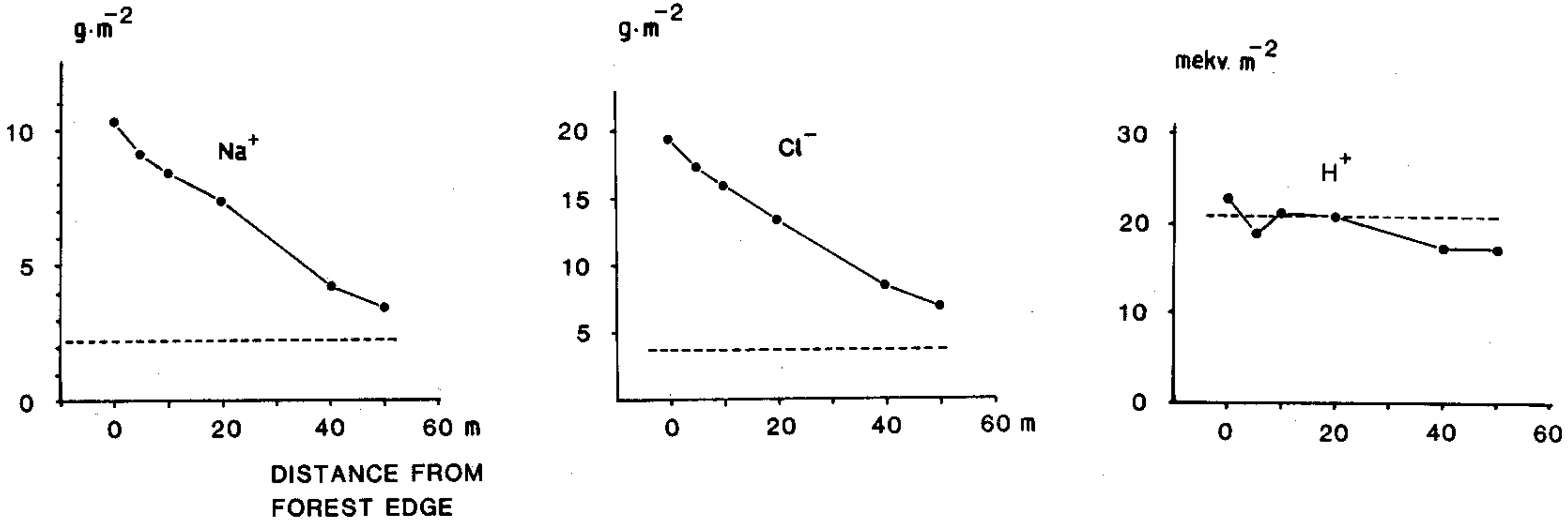


Figure 2 c). Results from the Swedish forest edge study, (Hasselrot & Grennfelt, 1987).

Throughfall deposition to forest floor of calcium, magnesium and potassium in a wind-exposed pine forest edge in SW Sweden. The continuous line represents the total deposition. The dotted lines represents the non-marine fraction (excess). The horizontal lines represent open-field sampling (bulk deposition) where the upper are the total and the lower are the non-marine fraction. Sampling were taken from June 27 to December 12, 1983.

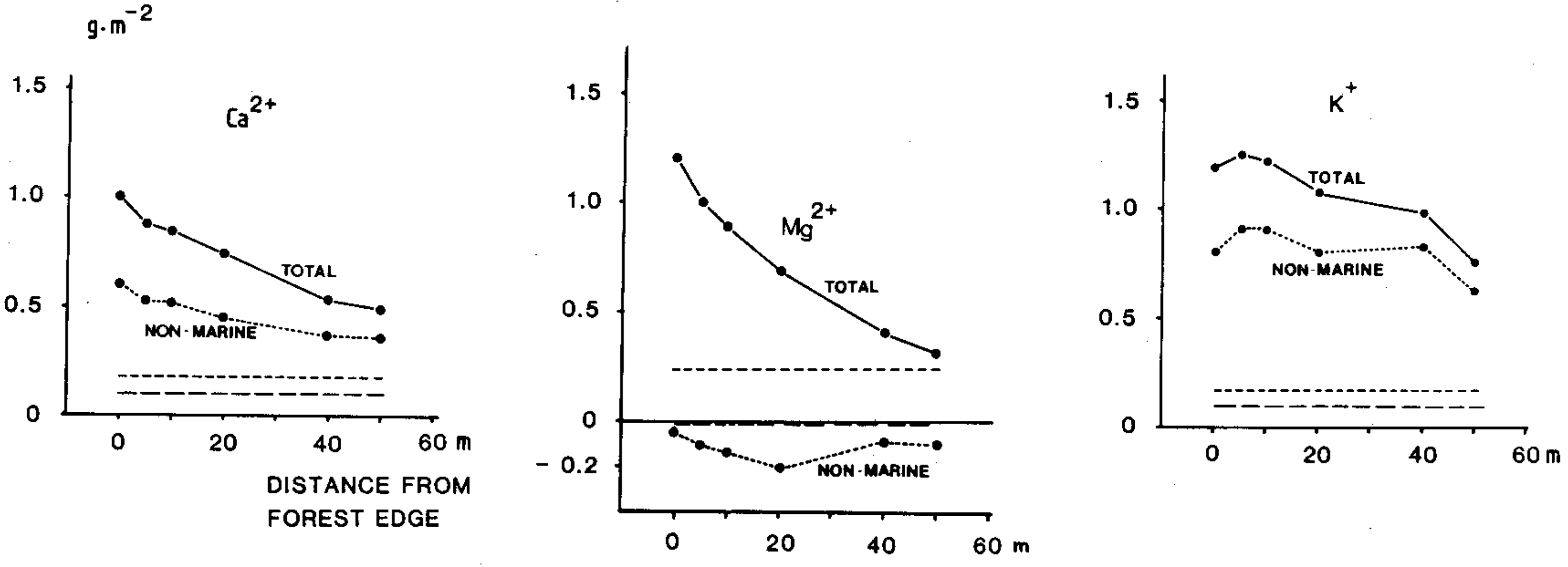
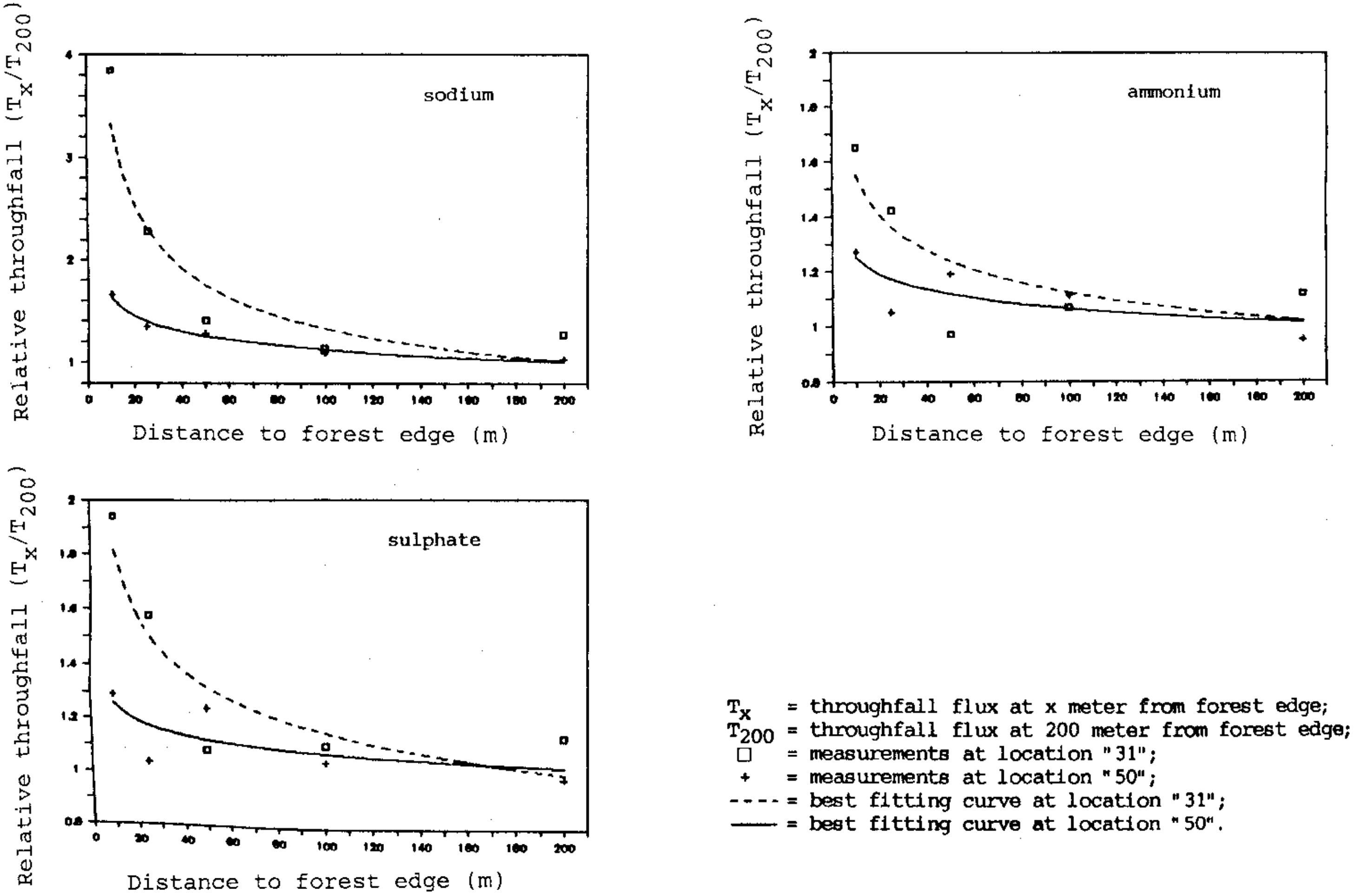


Figure 3. Throughfall at different distances from the forst edge in relation to throughfall 200 m inside the forest. (Ivens et al 1988)



6. DATA USED IN THE EVALUATION

6.1 General

Monitoring data from Europe have been found primarily via the literature. No systematic inquiries have been made to air pollution and forest authorities. As a consequence our data comes mainly from reports of different research projects. Largely we believe that this is a reflection of reality. There are, as far as we know, very few official monitoring networks in operation and those we know of have not been running for more than a few years (Norway, Finland, and some counties in Sweden).

Considering measurements of throughfall deposition, the deposition variability should be distinguished at different scales:

1. Within forest stands
   - In forest stands one can distinguish the trunk area and the canopy area. In the trunk area mainly water from stemflow is penetrating in the soil. In the canopy area mainly water dripping from the tree canopy or falling through gaps in the canopy is reaching the forest floor. Fluxes near the trunk can be up to 11 times higher than fluxes further away from the tree trunk (Ivens et al., 1989a). Throughfall fluxes vary from tree to tree due to differences in canopy structure (Ivens et al., 1988). In this study we do not consider these small-scale differences but these phenomena should not be overlooked when taking stand precipitation samples. Collecting representative samples of stand precipitation requires many random collectors or integrating pipe collectors (Ivens et al., 1988; Rasmussen, 1988).
   - Deposition processes at forest edges might be different from processes in the interior of forests, due to specific aerodynamic properties of forest edges (see Chapter 5).

2. Between stands
   - The stand structure influences the filtering capacity of the forest. Important parameters might be tree species (deciduous, coniferous), tree height, stand density and canopy density (see further section 3).
   - The aerodynamic strucure of the surroundings of the monitoring site.

3. Local/regional
   - Distance and exposure to sources of the air pollution is of great importance.

4. International
   - At this scale level the general emission patterns and meteorological conditions are of main importance.

To evaluate these effects we compiled two groups of throughfall data:

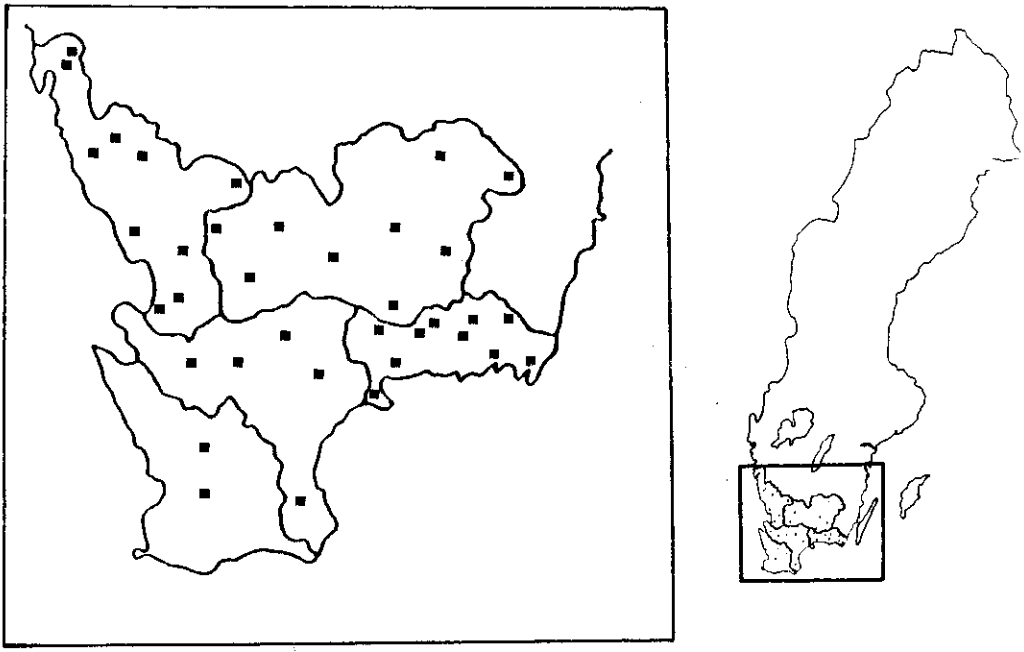
- The Swedish data set; containing data on throughfall inside forest stands from southern Sweden evaluated mainly in relation to forest and site characteristics.

- The European data set; containing data on throughfall within forest stands from European sites evaluated as long-term means (one or several years) and mainly in relation to kind of tree and pollution load.

6.2 Swedish data set

The Swedish data set (figure 4) contains throughfall results from four Swedish counties.

Fig. 4. Monitoring of throughfall in southern Sweden.
The Swedish data set.



During 1988, sampling of throughfall and bulk precipitation was made at 36 sites. Most of them were spruce stands (26 sites) but a few pine stands (7 sites) and deciduous stands (1 birch, 2 beech) were also represented (Table 3). The measurements were made on monthly basis all year round. The programme started 1986 and has been gradually extended. The following parameters have been determined in throughfall:

pH SO_4^{2-} NO_3^- NH_4^+ Cl^-

Stemflow has not been measured.

Sites and forest types are described by:

Kind of tree, age, height
Biomass (needles and branches) per ha
Number of trunks per ha
Altitude
Topography (class)
Wind exposure (class)

Table 3. Forest characteristics of the Swedish dataset.

Station	Year	Biomass (kgdw/ha)	Tree species*)	Forest age (years)	Forest height(m)	Trunks (per ha)
B 12 DAL	88	36672	1	57	24	500
B 22 GUN	88	26563	1	45	20	733
B 32 HJÄ	88	11042	2	50	15	744
B 42 HÅL	88	39244	1	78	29	367
B 52 ING	88	26571	1	45	15	811
B 62 HAM	88	38465	1	65	20	611
B 72 RYS	88		3	110	25	211
B 82 GAM	88	44242	1	35	17	1500
B 92 SKI	88	30852	1	55	18	800
B102 KAL	88	36037	1	55	21	566
H 12 SÖS	88	9468	2	61	22	544
H 22 ROS	88	35614	1	70	30	455
H 32 BRÄ	88	41592	1	72	28	538
H 42 MÄS	88	14141	2	85	20	567
H 52 NOR	88	36291	1	60	23	467
H 72 MAR	88	42732	1	60	24	555
H 82 MAG	88	47084	1	40	18	1150
H 92 AHL	88	38807	1	55	20	956
H102 SVA	88	13446	2	85	17	630
H112 FÄR	88					
K 12 LID	88	13840			20	
K 22 ORB	88	39680	1	54	23	611
K 32 BET	88	35279	1	52	23	722
K 52 ENE	88		3			
K 72 OSA	88	38497	1	80	24	478
K 82 KRO	88	39366	1	80	26	433
K 92 KNA	88	28063	1	30	13	1425
K102 NOT	88	12585	2	70	19	588
K112 GÖD	88	12834	2	73	22	422
S 12 TUN	88	29543	1	30	14	1283
S 22 DAL	88	39526	1	51	22	600
S 42 SKÅ	88		3	70	26	192
S 52 ARK	88	34693	1	30	13	1525
S 62 LUR	88	48278	1	25	13	2625
S 72 VTO	88	35820	1	40	17	1100
S 82 KLI	88	42638	1	50	22	622

*) 1 = spruce, 2 = pine, 3 = deciduous trees

6.3 European data set

Throughfall (stand precipitation) and bulk precipitation measurements carried out at 166 different sites in Europe were compiled from literature. No solitary bulk precipitation measurements were considered. Throughfall measurements differ greatly in a) duration of the measurement period, b) chemical parameters (ions) determined, and c) methods used, because they have been made with different goals in view. In this report, a selection of data has been made using the following criteria:

- The measurement period should be representative for a whole year. Data obtained from only one part of the year could give misleading results when extrapolated to annual figures. Due to this criteria many measurements of the Nordic monitoring programs (especially Finland and Norway, where stand precipitation is not collected in winter) have been excluded.

- The samples should be representative for the whole stand precipitation. This requires many collectors per sample site. Sites with only few collectors have been excluded.

- Measurements have to come from 1975 or later. Older data probably do not reflect the present day situation of deposition.

The general characteristics of the sites are given in Table 4. The data set includes a large part (29 sites) of the Swedish data set (IVL, 1989).

Table 4. General characteristics of the European dataset.

	NAME	NATION	LONG	LATT	PERIOD	REFERENCE
1	Vielsalm 1	B	5.55	50.17	(5)85-(4)86	Laitat & Fagot.1987
2	Vielsalm 2	B	5.55	50.17	(5)85-(4)86	Laitat & Fagot,1987
3	Alptal	CH	8.45	47.10	(6)86-(6)87	Kloti,1988
4	Laegern 1	CH	8.22	47.29	(6)86-(6)87	Kloti.1988
5	Laegern 2	CH	8.22	47.29	(6)86-(6)87	Kloti.1988
6	Davos	CH	9.50	46.48	(6)86-(6)87	Kloti.1988
7	Konigstein	D	8.28	50.11	(1)83-(6)85	Georgii et al.,1986
8	Grebenau	D	9.29	50.45	(1)83-(6)85	Georgii et al.,1986
9	Witzenhausen	D	9.51	51.20	(1)83-(6)85	Georgii et al.,1986
10	Solling 1	D	9.25	51.45	1969-1985	Bredermeier,1988
11	Solling 2	D	9.25	51.45	1969-1985	Bredermeier,1988
12	Heide 1	D	10.00	53.00	1980-1985	Bredermeier,1988
13	Heide 2	D	10.00	53.00	1980-1985	Bredermeier,1988
14	Schonbuch 1	D	9.10	48.30	1979-1983	Bueking & Steinle,1988
15	Schonbuch 2	D	9.10	48.30	1979-1983	Bueking & Steinle.1988
16	Feldberg 1	D	8.02	47.51	1986	Bueking & Steinle.1988
17	Feldberg 2	D	8.02	47.51	1986	Bueking & Steinle.1988
18	Wingst	D	9.02	53.43	1983	Bredermeier.1988
19	Harz	D	10.25	51.45	1983	Bredermeier.1988
20	Hils	D	9.40	52.00	1984-1985	Bredermeier,1988
21	Harste	D	9.50	51.35	1982-1985	Bredermeier,1988
22	Spanbeck	D	10.50	51.35	1982-1985	Bredermeier.1988
23	Oberwarmenst. 1	D	11.47	49.59	(7)84-(6)86	Hantschl,1987
24	Wuelfersreuth	D	11.46	50.04	(7)84-(6)86	Hantschl,1987
25	Klosterhede	DK	8.25	56.28	1985-1987	Rasmussen.1988
26	Tange	DK	9.25	56.21	1985-1987	Rasmussen,1988
27	Strodam	DK	12.19	55.56	1985-1987	Rasmussen,1988
28	Ulborg 1	DK	8.26	56.17	(6)85-(6)86	Hovmand & Bille-Hansen,1988
29	Ulborg 2	DK	8.26	56.17	(6)85-(6)86	Hovmand & Bille-Hansen.1988
30	Frederiksborg 1	DK	12.21	55.57	(6)85-(6)86	Hovmand & Bille-Hansen,1988
31	Frederiksborg 2	DK	12.21	55.57	(6)85-(6)86	Hovmand & Bille-Hansen.1988
32	Aubure	F	7.00	48.02	(10)86-(9)87	Probst & Dambrine,1988
33	Tillingbourne 1	GB	-0.20	51.10	1981	Skeffington,1983
34	Tillingbourne 2	GB	-0.20	51.10	1981	Skeffington,1983
35	Tillingbourne 3	GB	-0.20	51.10	1981	Skeffington.1983
36	Kilmichael	GB	-5.28	56.05	(4)75-(4)77	Miller & Miller,1980
37	Leanachan	GB	-4.50	56.50	(4)75-(4)77	Miller & Miller,1980
38	Strathyre	GB	-4.19	56.19	(4)75-(4)77	Miller & Miller.1980
39	Kershope	GB	-2.50	55.10	(4)75-(4)77	Miller & Miller,1980
40	Elibank	GB	-2.50	55.40	(4)75-(4)77	Miller & Miller,1980
41	Fetteresso	GB	-2.20	56.55	(4)75-(4)77	Miller & Miller,1980
42	Edinburgh	GB	-3.30	55.50	1979	Nicholson et al.,1980
43	Ascot 1	GB	-0.68	51.10	(9)76-(9)77	Alcock & Morton,1981,1985
44	Ascot 2	GB	-0.68	51.10	(9)76-(9)77	Alcock & Morton,1981.1985
45	Beddgelert 1	GB	-4.12	53.08	(6)84-(6)85	Stevens,1987
46	Beddgelert 2	GB	-4.12	53.08	(6)84-(6)85	Stevens,1987
47	Nedstrand	N	5.48	59.2	(1)88-(12)88	NISK,1989
48	Winterswijk 1	NL	6.44	51.58	(11)81-(11)82	Verstraten et al.,1984
49	Winterswijk 2	NL	6.44	51.58	(11)81-(11)82	Verstraten et al.,1984

- continued -

50	Hackfort	NL	6.14	52.05	(4)81-(4)82	v.Breemen et al.,1988
51	Campina	NL	5.15	51.35	1981	v.Breemen et al.,1982
52	Kootwijk	NL	5.46	52.11	(10)85-(10)87	Ivens et al.,1988
53	Garderen	NL	5.43	52.14	(5)87-(5)88	Kleijn et al.,1989
54	Zelhem 1	NL	6.21	52.00	(5)87-(5)88	Kleijn et al.,1989
55	Gardsjon	S	11.30	58.00	(10)80-(9)81	Grennfelt et al.,1985
56	Sodra Vam	S	13.06	56.03	(10)84-(9)85	Grennfelt & Hasselrot,1987
57	Tonnersjo	S	13.06	56.42	(10)84-(9)85	Grennfelt & Hasselrot,1987
58	Ydrefors	S	15.33	57.49	(10)84-(9)85	Grennfelt & Hasselrot,1987
59	Hultasvagen	S	12.22	57.16	(12)84-(12)85	Alenas & Skarby, 1988a,b
60	Dalanshult	S			(1)86-(12)88	IVL,1989
61	Gungvala	S			(1)86-(12)88	IVL,1989
62	Hjartsjomala	S			(1)86-(12)88	IVL,1989
63	Halaback	S			(1)86-(12)88	IVL,1989
64	Inglatorp	S			(1)86-(12)88	IVL,1989
65	Hammarby	S			(1)86-(12)88	IVL,1989
66	Ryssberget	S			(1)86-(12)88	IVL,1989
67	Gammelstorp	S			(1)86-(12)88	IVL,1989
68	Skillingsmala	S			(1)86-(12)88	IVL,1989
69	Kallgardsmala	S			(1)86-(12)88	IVL,1989
70	Sostared	S			(1)88-(12)88	IVL,1989
71	Rossared	S			(1)88-(12)88	IVL,1989
72	Branhult	S			(1)88-(12)88	IVL,1989
73	Mashult	S			(1)88-(12)88	IVL,1989
74	Normanstorp	S			(1)88-(12)88	IVL,1989
75	Marback	S			(1)88-(12)88	IVL,1989
76	Margreteberg	S			(1)88-(12)88	IVL,1989
77	Ahla	S			(1)88-(12)88	IVL,1989
78	Svarvareskogen	S			(1)88-(12)88	IVL,1989
79	Farda	S			(1)88-(12)88	IVL,1989
80	Lidhult	S			(1)87-(12)88	IVL,1989
81	Orberg	S			(1)87-(12)88	IVL,1989
82	Beteras	S			(1)87-(12)88	IVL,1989
83	Eneryda	S			(1)87-(12)88	IVL,1989
84	Osaby	S			(1)87-(12)88	IVL,1989
85	Krokshult	S			(1)87-(12)88	IVL,1989
86	Knapanas	S			(1)87-(12)88	IVL,1989
87	Notteback	S			(1)87-(12)88	IVL,1989
88	Godeshult	S			(1)87-(12)88	IVL,1989

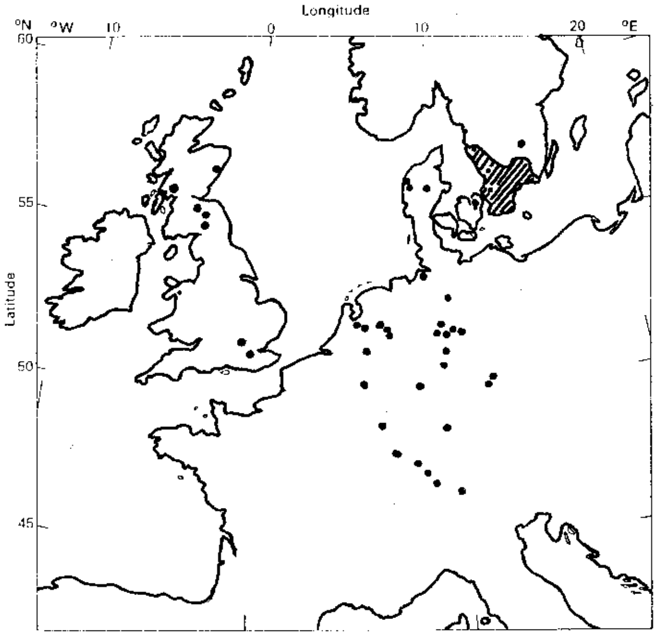
6.3.1 Geographical distribution of measurement sites

The sites are not distributed evenly over Europe (fig. 5), 91% of the sites are concentrated in 5 countries (Sweden, Federal Republic of Germany, United Kingdom, Denmark and The Netherlands). Even within countries, the distribution is very uneven. In The Netherlands 7 of the 8 sites are located in the same county, and in Sweden all sites are in the southern part of the country.

Figure 5. Throughfall monitoring stations in Europe*.
"European data set".

▨ Area of the "Swedish dataset". See fig.1.

* When two or more stations are located within a few km from eachother, they are represented by only one dot.



6.3.2 Chemical parameters determined

At nearly all sites sulphur fluxes have been measured (Table 5).

Table 5. Number of sites with throughfall measurements per ion.

Ion	SO_4^{2-}	NO_3^-	Cl^-	NH_4^+	Na^+	K^+	Ca^{2+}	Mg^{2+}	H^+
Sites	84	78	67	73	43	43	49	48	67

Ammonium and nitrate have been measured at 73 sites and 78 sites, respectively. Potassium, calcium and magnesium have been measured at about half of the sites.

A part of the stand precipitation is due to deposition of sea-salt particles. These are neutral salts, which do not contribute to acidic (in case of sulphur) reactions in the forest soil. Ion fluxes in bulk and stand precipitation can be corrected for the contribution of sea salt particles, using sodium or chloride as sea salt tracers (Asman et al., 1983). The importance of this correction can be illustrated by the fact that calculated sea-salt contribution to the total sulphur flux in stand precipitation was 7.9%. Sea-salt contributions up to 45% of the total sulphur in stand precipitation were found at coastal sites.

At 13 locations (10 of them within 200 km from the sea coast) both sodium and chloride were not measured in stand precipitation For these location it is not possible to estimate the contribution of sea-salts directly from the data.

6.3.3 Site characteristics

The major part of the forest stands (82%) was formed by conifers, especially spruce (Table 6).

Table 6. Tree species in the European dataset

Coniferous		Deciduous	
Spruce	55	Beech	8
Pine	12	Oak	2
Fir	3	Birch	3
Mixed	2*	Maple	1
		Mixed	2
Total	72	Total	16

*one site contains some deciduous trees

Stand characteristics are given in table 7.

The data set gives information on tree species and stand age, but lacks sufficient data on other forest stand characteristics. Only the Swedish data gives a quite good information (age, height, tree density, canopy biomass of conifers). Therefore, the relationship between stand characteristics and throughfall will be discussed separately for the Swedish data.

The data set is also lacking systematic information on exposure of the sites and aerodynamic structure of the surroundings of the monitoring sites.

Table 7. Stand characteristics of the European dataset.

	NAME	SP	AGE yr	HEIGHT m	DENSITY trees/ha	DBH cm	CAN. COV. %	remarks
1	Vielsalm 1	1	ca. 30					
2	Vielsalm 2	1	ca. 90					
3	Alptal	1						
4	Laegern 1	1	100-130					
5	Laegern 2	11	100-130	ca. 35				
6	Davos	1		25-30				
7	Konigstein	1	60-80					
8	Grebenau	1	60-80					
9	Witzenhausen	1	60-80					
10	Solling 1	11	138					
11	Solling 2	1	103					
12	Heide 1	12	105					
13	Heide 2	2	100					
14	Schonbuch 1	1	60	25-30	1041			
15	Schonbuch 2	11	80	20-35	275			
16	Feldberg 1	1	120-150					
17	Feldberg 2	15						
18	Wingst	1	95					
19	Harz	1	40					
20	Hils	1	100					
21	Harste	11	96					
22	Spanbeck	11	86					
23	Oberwarmenst. 1	1	40					
24	Wuelfersreuth	1	40					
25	Klosterhede	1	67		858			
26	Tange	1	46					
27	Strodam	1	41					
28	Ulborg 1	11	26	6.4	3696	6.6		
29	Ulborg 2	1	26	7.7	2814	9.0		
30	Frederiksborg 1	11	26	9.7	2133	9.6		
31	Frederiksborg 2	1	26	12.3	1802	13.3		
32	Aubure	1	80					
33	Tillingbourne 1	12	40-50	11-18				
34	Tillingbourne 2	13	40-50	11-18				
35	Tillingbourne 3	2	40-50	11-18				
36	Kilmichael	1	25-30					
37	Leanachan	1	25-30					
38	Strathyre	1	25-30					
39	Kershope	1	25-30					
40	Elibank	1	25-30					
41	Fetteresso	1	25-30					
42	Edinburgh	2	27	9-10	4000			
43	Ascot 1	13	30		1670			
44	Ascot 2	2	30		2542			
45	Beddgelert 1	1	48	16	800	26		
46	Beddgelert 2	1	33	13	3900	16		
47	Nedstrand	1	50					
48	Winterswijk 1	11,12						
49	Winterswijk 2	3,12						

- continued -

50	Hackfort	17,18			550-1110			
51	Campina	2						
52	Kootwijk	4	39-64	14-24	314-860	10.1-16.4	75-96	
53	Garderen	4	37		520			
54	Zelhem 1	4	44		248			
55	Gardsjon	1	80				100	
56	Sodra Vam	1	40	10-15				
57	Tonnersjo	1	87	25-30				
58	Ydrefors	1,2	60	12-15				
59	Hultasvagen	1	60-80	24				
60	Dalanshult	1	57	24	500			bm
61	Gungvala	1	45	20	733			bm
62	Hjartsjomala	2	50	15	744			bm
63	Halaback	1	78	29	367			bm
64	Inglatorp	1	45	15	811			bm
65	Hammarby	1	65	20	611			bm
66	Ryssberget	11	110	25	211			
67	Gammelstorp	1	35	17	1500			
68	Skillingsmala	1	55	18	800			bm
69	Kallgardsmala	1	55	21	566			
70	Sostared	2	61	22	544			bm
71	Rossared	1	70	30	455			bm
72	Branhult	1	72	28	538			bm
73	Mashult	2	85	20	567			bm
74	Normanstorp	1	60	23	467			bm
75	Marback	1	60	24	555			bm
76	Margreteberg	1	40	18	1150			bm
77	Ahla	1	55	20	956			bm
78	Svarvareskogen	2	85	17	630			bm
79	Farda	1	81					
80	Lidhult	2	70					
81	Orberg	1	54		611			
82	Beteras	1	52		722			
83	Eneryda	13	25					
84	Osaby	1	80		478			
85	Krokshult	1	90		433			
86	Knapanas	1	30		1425			
87	Notteback	2	70		588			
88	Godeshult	2	73		422			

Explanation of codes

SP = tree species: 1=Picea; 2=Pinus; 3=Abies; 4=Pseudotsuga; 11=Fagus
12=Quercus; 13=Betulus; 15=Acer; 17=Alnus; 18=Populus

HEIGHT = tree height

DENSITY = amount of stems per hectare

DBH = diameter of tree stem at breast height

CAN. COV. = percentual canopy coverage

bm = measure of aboveground biomass

6.3.4 Contribution of stemflow to total stand precipitation

At 64 sites stemflow (SF) was not accounted for in the total stand precipitation (SP). The importance of stemflow depends on tree species and stand age and can be estimated according to the formula:

$$SF = \alpha \cdot SP$$

In table 8 rough estimates for α are given, which have been derived from data in literature (Alcock & Morton, 1985; Ivens et al., 1988; Johnson et al., 1986; Laitat & Fagot, 1987; Mayer, 1987; Miller & Miller, 1989; Nicholson et al., 198 ; Nihlgard, 1970; Rapp. 1971; Rapp. 1973; Van Breemen et al., 1989; Verstraten et al., 1984). In general, stemflow can not be neglected for deciduous stands and young coniferous stands. Total stand precipitation might be underestimated up to 30% in such sites when stemflow is not taken into account. The contribution of stemflow to the total flux to the forest floor was shown to be more important for free acidity (H^+) than for other ions.

Table 8. Values of parameter α (-).

Tree species	Age (years)	SO_4^{2-}	NO_3^-	Cl^-	NH_4^+	Na^+	Ca^{2+}	Mg^{2+}	H^+
deciduous	all	0.12							0.26
coniferous	<20	0.24							0.50
coniferous	20-90	0.31-0.034*age							0.64-0.07*age
coniferous	>90	0.00							0.00

7. RESULTS FROM EVALUATION OF THE SWEDISH AND THE EUROPEAN DATA SET

7.1 Spatial variations in throughfall of sulphur and nitrogen in southern Sweden

Data from a deposition monitoring network in southern Sweden (based on throughfall) show considerably higher sulphur deposition levels and also larger variations than first expected (figure 6, Westling 1989).

A certain variability is expected due to uncertainties involved in sampling and analysis. The variability observed over southern Sweden is, however, to a major part due to variations in dry deposition. The wet deposition varies less, between 8-11 kg S/ha^{-1} ·year. The variation in ratio between throughfall and bulk precipitation will reflect the variation in dry deposition (figure 7). The dry deposition variations are to a major extent due to differences in forest structure and site. There are no large variations of sulphur in air pollution over the area.

For nitrogen (NO_3^--N and NH_4^+-N (figure 8 and 9) there is a difference in forest structure but also a difference due to local emission and load of nitrogen. This will affect the deposition as well as the nutrient status of the trees.

The relation between throughfall and bulk precipitation is seen in figure 10 and 11. It is obvious that there is a "coastal" effect with respect to nitrogen load. This might be caused for example by

- larger local emission and load due to agricultural activities on the lowlands near the coast,

- larger exposures to reactive long-range transported air pollutants, such as gaseous nitric acid.

Figure 6. Excess sulphur in throughfall (kgS $ha^{-1}yr^{-1}$).
The Swedish dataset.

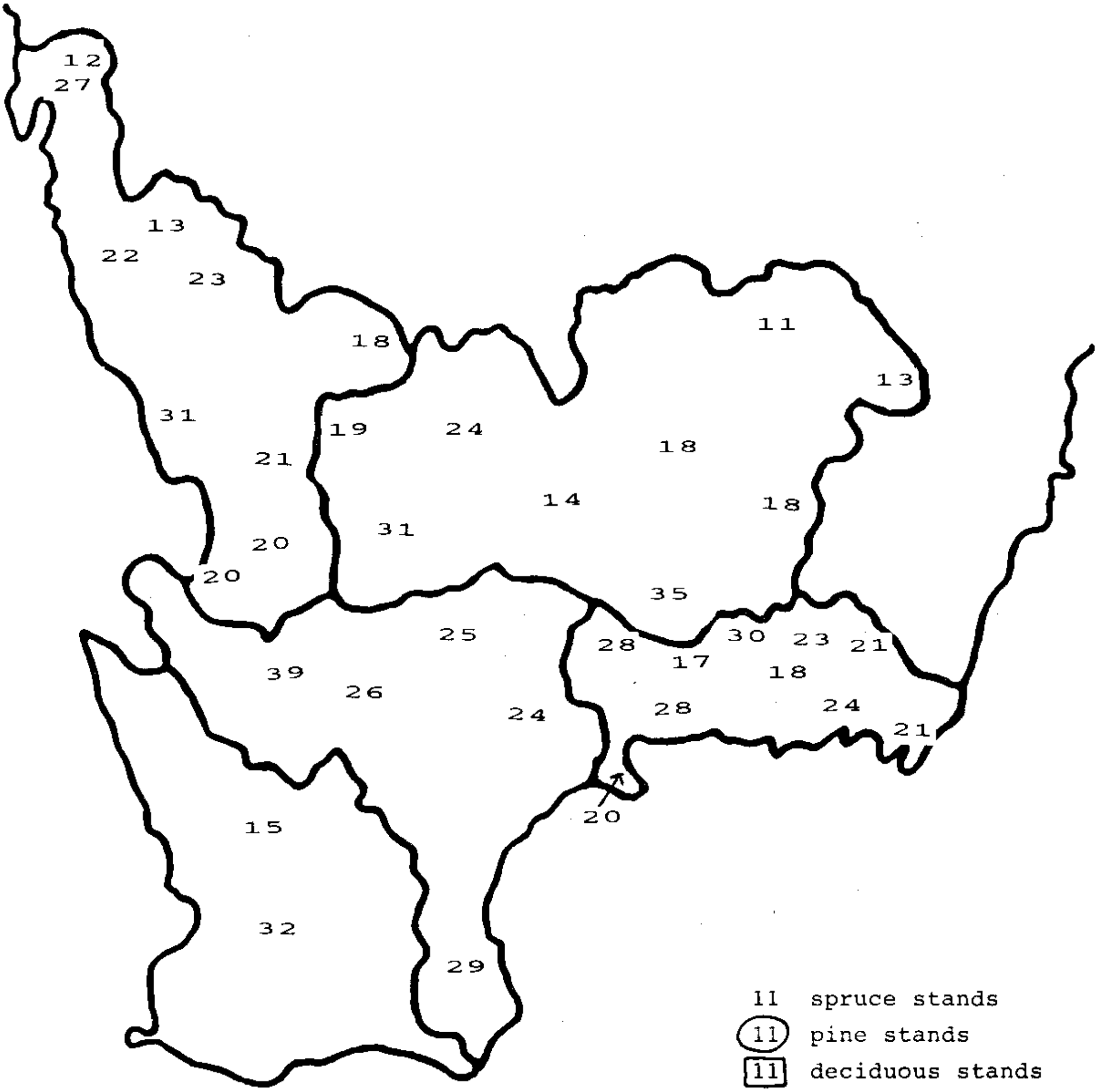


Figure 7. Ratio between throughfall and bulk precipitation of sulphur. The Swedish dataset.

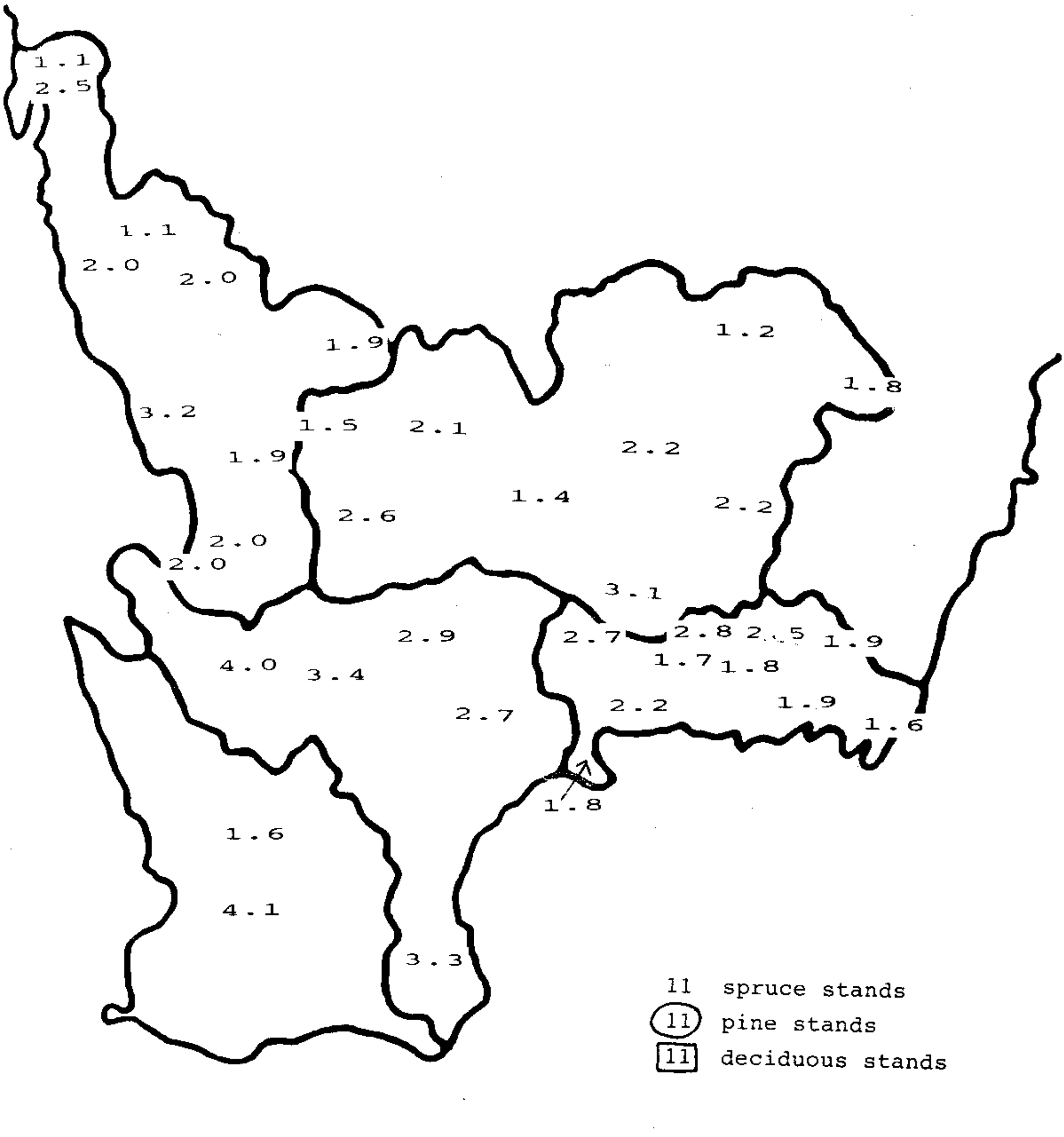


Figure 8. Nitrate in throughfall (kg N.ha^{-1}year^{-1}). The Swedish dataset 1988.

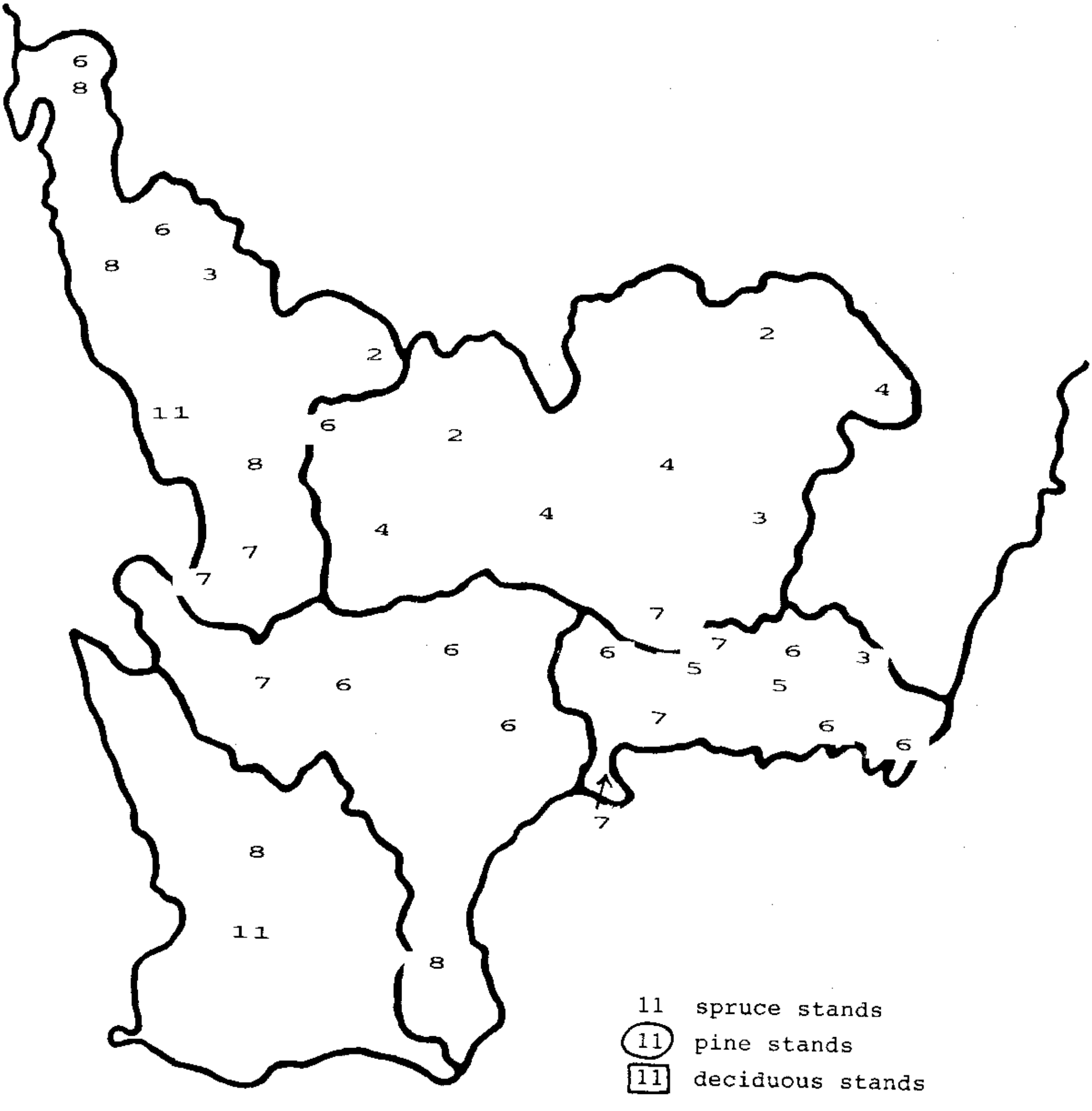


Figure 9. Ammonium in throughfall (kg N.ha^{-1}.year^{-1}). The Swedish dataset 1988.

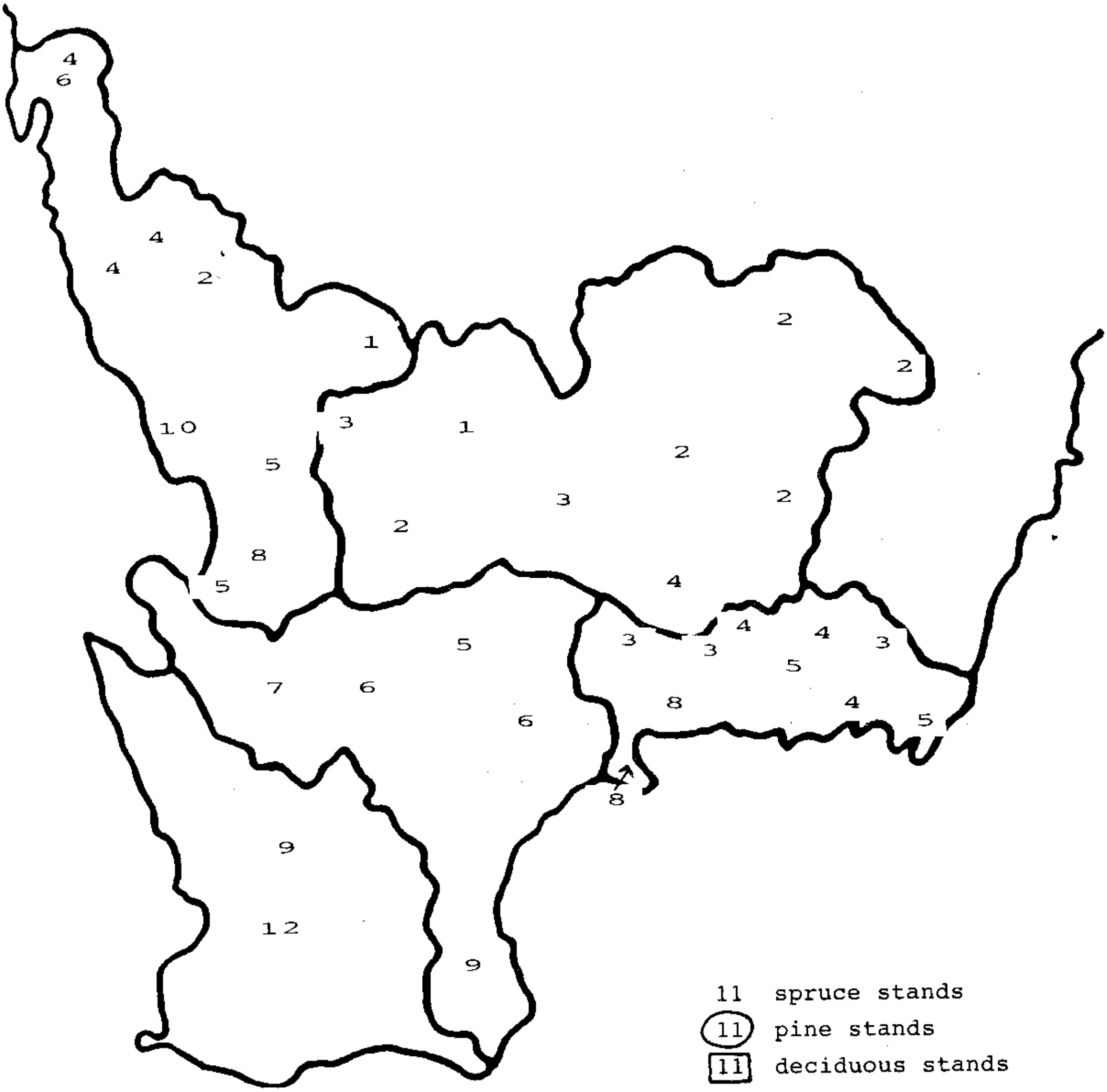


Figure 10. Ratio between througfall and bulk deposition of nitrate (NO_3^--N). Swedish dataset 1988.

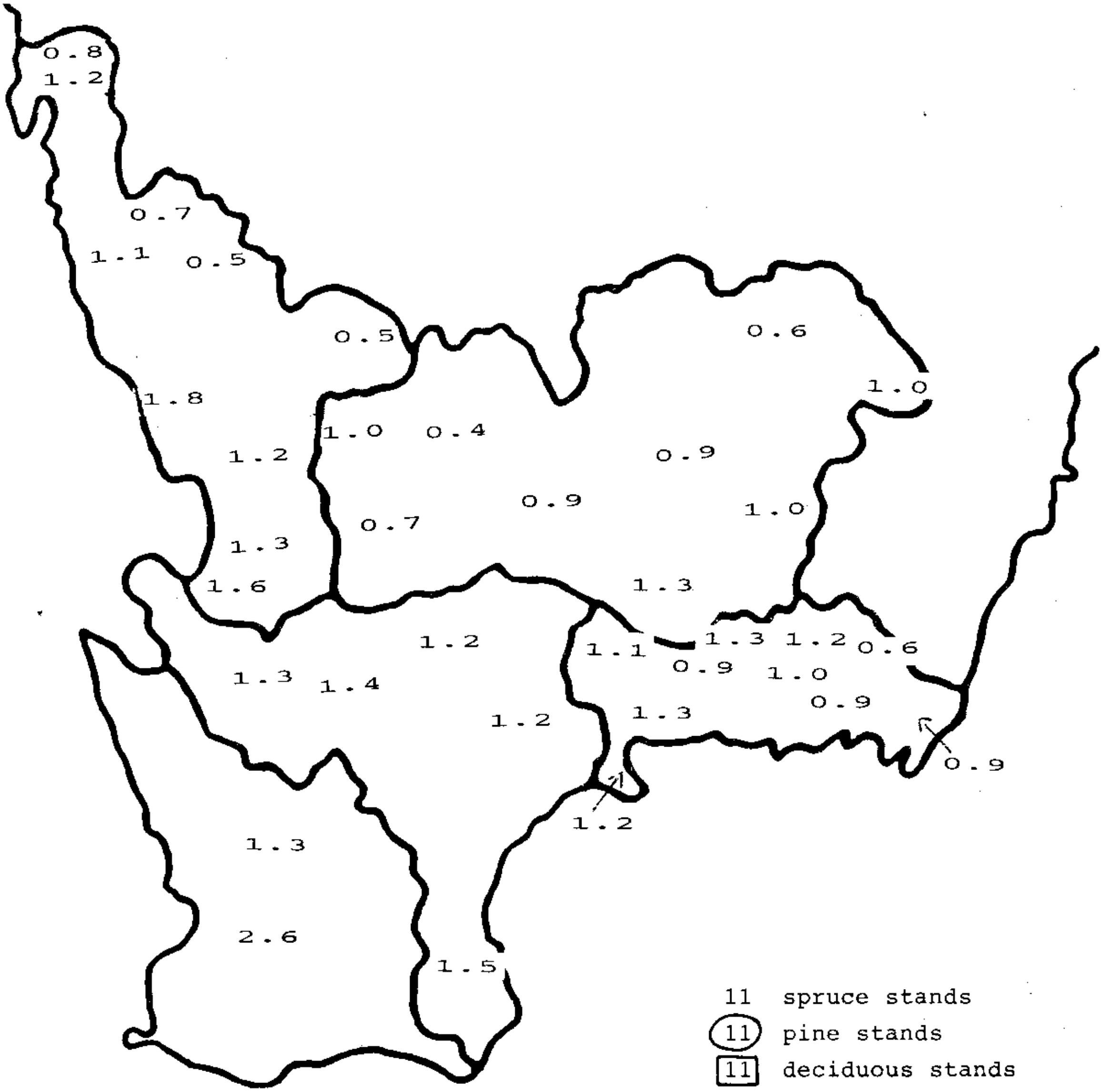
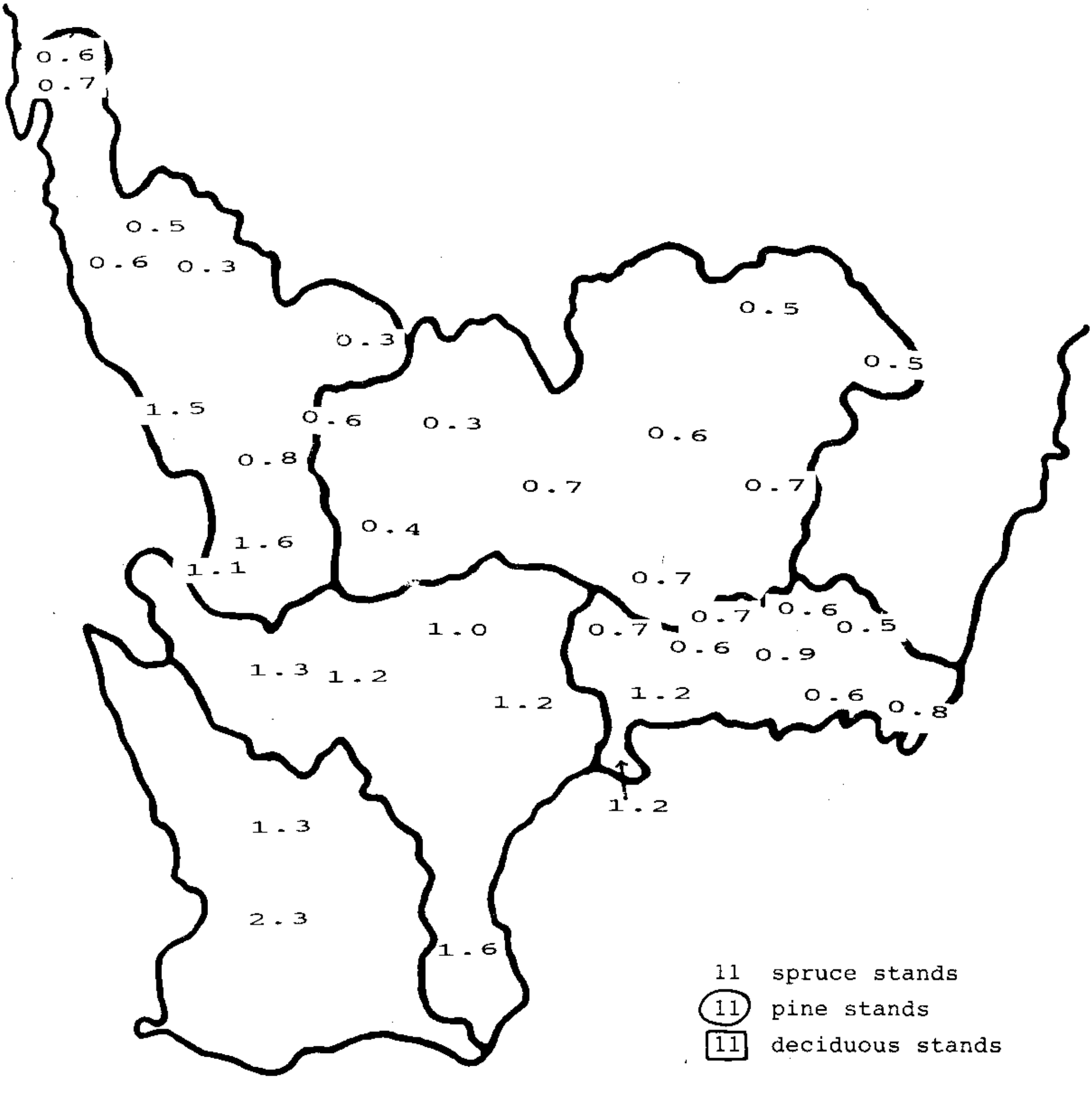


Figure 11. Ratio between throughfall and bulk deposition of ammonium (NH_4^+-N). Swedish dataset 1988.



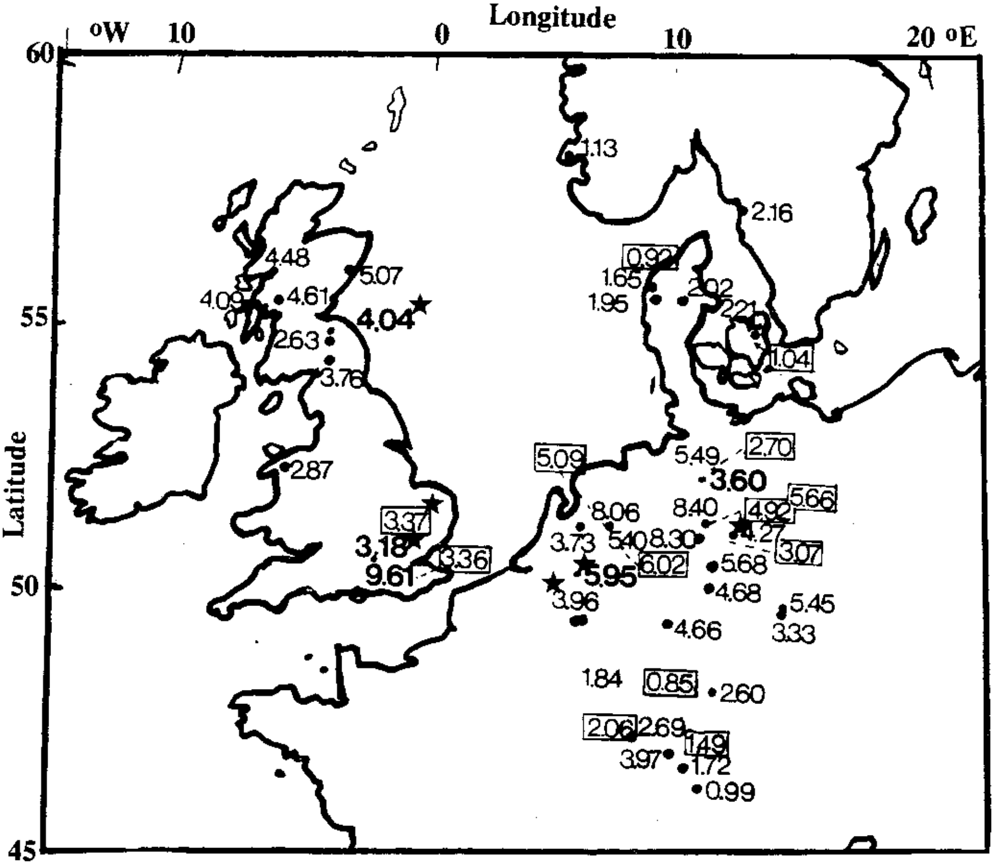


Figure 12.
Stand precipitation of sulphur in European forest stands, g S $m^{-2} yr^{-1}$.

8 spruce stands
8 pine
$\boxed{8}$ deciduous
★ no correction for sea salt

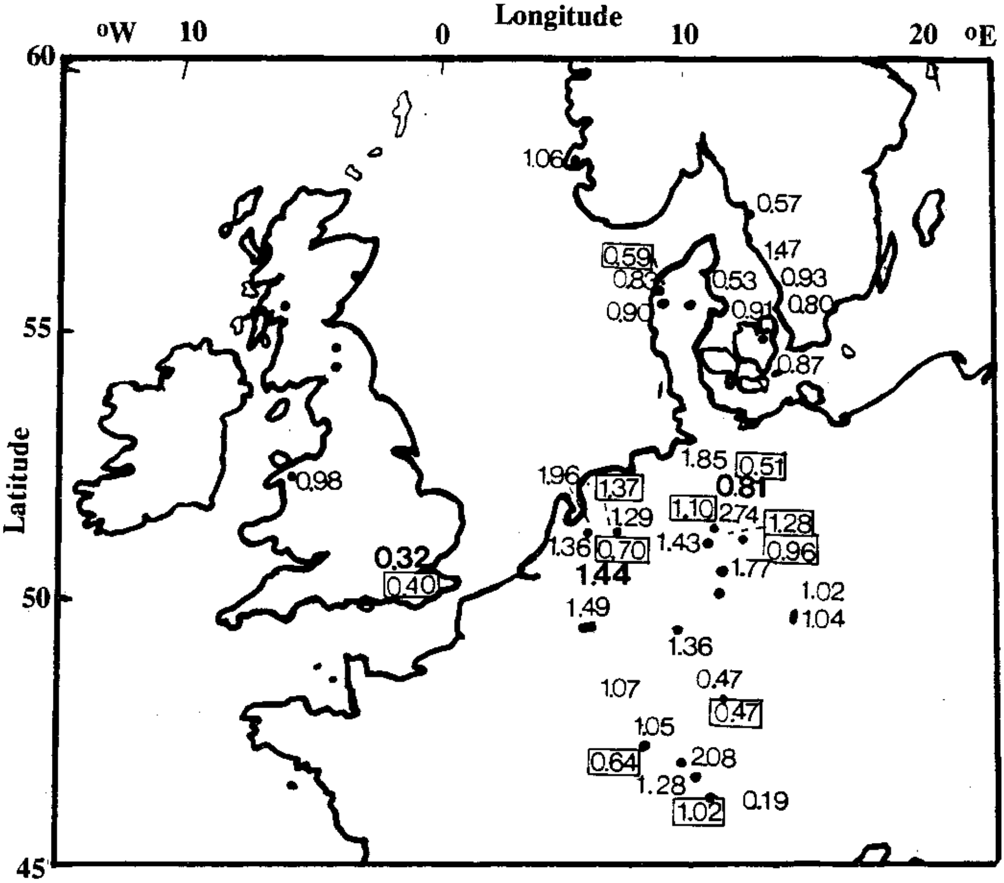


Figure 13.
Stand precipitation of nitrate in European forest stands, g N $m^{-2} yr^{-1}$. Different forest stands are marked as in figure 12.

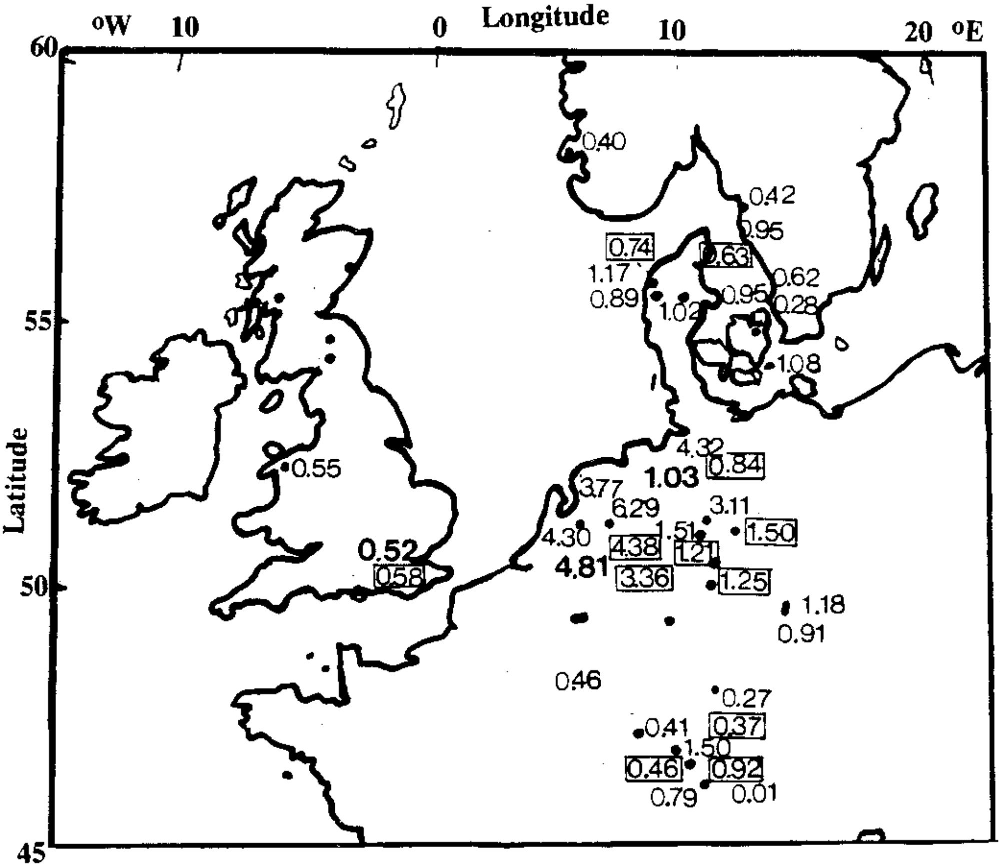


Figure 14.
Stand precipitation of ammonium in European forest stands, g N $m^{-2}yr^{-1}$. Different forest stands are marked as in figure 12.

Table 9. Bulk precipitation data from the European dataset.

	NAME	S-SO4	N-NO3	Cl	N-NH4	Na	K	Ca	Mg	H
1	Vielsalm 1	1.64	0.60							0.003
2	Vielsalm 2	1.64	0.60							0.003
3	Alptal	1.15	0.83	0.62	0.66	0.29		0.32	0.07	
4	Laegern 1	0.99	0.46	0.44	0.45	0.17		0.19	0.03	
5	Laegern 2	0.99	0.46	0.44	0.45	0.17		0.19	0.03	
6	Davos	0.29	0.25	0.18	0.12	0.07		0.18	0.03	
7	Konigstein	1.27	0.37	1.12		0.58	0.37	0.54	0.18	0.022
8	Grebenau	1.19	0.39	0.75		0.45	0.47	0.39	0.08	0.043
9	Witzenhausen	1.66	0.54	1.05		0.62	1.55	0.70	0.13	0.043
10	Solling 1	2.38	0.85	1.71	1.20	0.82	0.35	1.00	0.16	0.080
11	Solling 2	2.38	0.85	1.71	1.20	0.82	0.35	1.00	0.16	0.080
12	Heide 1	1.69	0.68	2.60	1.02	1.40	0.42	0.50	0.21	0.026
13	Heide 2	1.69	0.68	2.60	1.02	1.40	0.42	0.50	0.21	0.026
14	Schonbuch 1	0.76	0.41	0.77	0.38	0.39	0.24	0.94	0.09	0.037
15	Schonbuch 2	0.72	0.25	0.58	0.42	0.36	0.44	0.44	0.08	0.021
16	Feldberg 1	1.33	0.65	1.40	0.71	0.63	0.47	0.43	0.11	0.043
17	Feldberg 2	1.33	0.65	1.40	0.71	0.63	0.47	0.43	0.11	0.043
18	Wingst	1.62	0.89	5.63	1.55	3.40		0.58	0.42	0.020
19	Harz	2.24	0.75	1.82	1.22	1.03		0.64	0.29	0.080
20	Hils	1.51	0.72	1.30	0.86	1.25		0.54	0.06	0.050
21	Harste	1.30	0.60	1.04	0.63	0.49		1.03	0.15	0.030
22	Spanbeck	1.47	0.61	0.97	0.52	0.50		0.99	0.10	0.040
23	Oberwarmenst. 1	2.43	0.97		0.86		0.73	0.74	0.19	0.061
24	Wuelfersreuth	1.38	1.06		0.90		0.64	0.85	0.19	0.059
25	Klosterhede	1.53	0.71	9.50	0.62	5.30	0.25	0.33	0.54	0.041
26	Tange	0.93	0.51	4.00	0.90	2.20	0.28	0.33	0.24	0.019
27	Strodam	1.03	0.70	3.00	0.59	1.70	0.14	0.28	0.16	0.041
28	Ulborg 1	1.30	0.56	9.40	0.64	5.60	0.34	0.33	0.63	0.028
29	Ulborg 2	1.30	0.56	9.40	0.64	5.60	0.34	0.33	0.63	0.028
30	Frederiksborg 1	0.99	0.52	2.30	0.58	1.20	0.20	0.33	0.15	0.029
31	Frederiksborg 2	0.99	0.52	2.30	0.58	1.20	0.20	0.33	0.15	0.029
32	Aubure	0.95		0.71		0.35	0.14	0.30	0.08	
33	Tillingbourne 1	1.44	0.53	3.27	0.63					0.064
34	Tillingbourne 2	1.44	0.53	3.27	0.63					0.064
35	Tillingbourne 3	1.44	0.53	3.27	0.63					0.064
36	Kilmichael	3.00				4.10	0.14	1.00	0.43	
37	Leanachan	2.70				3.30	0.21	1.10	0.36	
38	Strathyre	2.90				2.50	0.24	0.70	0.26	
39	Kershope	2.20				2.20	0.20	1.00	0.30	
40	Elibank	1.40				2.10	0.22	0.70	0.27	
41	Fetteresso	2.80				3.50	0.18	0.90	0.49	
42	Edinburgh	1.35						0.56	0.40	0.050
43	Ascot 1	3.93					0.28	4.34	0.24	
44	Ascot 2	3.93					0.28	4.34	0.24	
45	Beddgelert 1	2.06	0.56	10.43	0.54	5.80	0.25	0.83	0.67	0.079
46	Beddgelert 2	2.06	0.56	10.43	0.54	5.80	0.25	0.83	0.67	0.079
47	Nedstrand	1.22	0.53	6.29	0.34	4.09	0.35	0.50	0.36	0.058
48	Winterswijk 1	1.84	0.59	1.90	1.47	0.92	0.36	0.79	0.20	0.012
49	Winterswijk 2	1.00	0.59	1.90	1.47	0.92	0.36	0.79	0.20	0.012

- continued -

50 Hackfort	2.08	0.76	3.20	1.67	2.02	0.20	0.78	0.26	0.019
51 Campina	1.65	0.60		1.08					0.049
52 Kootwijk	1.64	0.52	2.94	1.41	1.08	0.45	0.88	0.19	0.031
53 Garderen	1.22	0.65		2.17	1.68	0.88	0.27	0.19	
54 Zelhem 1	1.10	0.63		1.95	1.35	1.12	0.32	0.18	
55 Gardsjon	0.95	0.34	2.50	0.49	1.34	0.05	0.12	0.16	
56 Sodra Vam		0.36		0.52					
57 Tonnersjo		0.77		0.79					
58 Ydrefors		0.59		1.00					
59 Hultasvagen		0.94		0.97					0.065
60 Dalarshult	0.99	0.45	0.75	0.48					0.051
61 Gungvala	1.08	0.48	0.68	0.53					0.041
62 Hjartsjomala	0.94	0.44	0.63	0.44					0.048
63 Halaback	0.91	0.45	0.60	0.47					0.046
64 Inglatorp	1.01	0.48	0.65	0.57					0.046
65 Hammarby	1.04	0.48	0.64	0.54					0.040
66 Ryssberget	0.98	0.44	0.65	0.50					0.040
67 Gammelstorp	0.91	0.43	0.54	0.52					0.039
68 Skillingsmala	0.87	0.42	0.50	0.47					0.044
69 Kallgardsmala	0.89	0.43	0.50	0.46					0.044
70 Sostared	1.20	0.71	2.20	0.68					0.089
71 Rossared	1.16	0.66	2.84	0.76					0.068
72 Branhult	1.22	0.71	2.40	0.63					0.094
73 Mashult	1.27	0.75	2.49	0.69					0.095
74 Normanstorp	1.15	0.62	2.09	0.59					0.081
75 Marback	1.19	0.65	2.34	0.68					0.076
76 Margreteberg	1.06	0.59	2.89	0.58					0.069
77 Ahla	1.07	0.54	2.18	0.51					0.059
78 Svarvareskogen	1.11	0.49	2.34	0.44					0.064
79 Farda	0.97	0.47	1.52	0.39					0.073
80 Lidhult	1.58	0.50	1.52	0.48					0.052
81 Orberg	1.02	0.45	1.02	0.29					0.046
82 Beteras	1.25	0.52	1.97	0.55					0.069
83 Dreryda	0.90	0.40	0.88	0.35					0.043
84 Osaby	0.78	0.34	0.58	0.33					0.037
85 Kackshult	0.97	0.42	0.64	0.45					0.042
86 Knapanas	0.76	0.30	0.45	0.31					0.032
87 Notteback	0.82	0.36	0.53	0.33					0.039
88 Godeshult	0.74	0.32	0.34	0.31					0.033

Table 10. Stand precipitation data from the European dataset.

NAME	S-SO4	N-NO3	Cl	N-NH4	Na	K	Ca	Mg	H	remark
1 Vielsalm 1	3.27	1.10							0.013	t+s
2 Vielsalm 2	4.64	1.88							0.013	t+s
3 Alptal	1.74	1.28	0.82	0.79	0.29	1.58	1.18	0.16		t
4 Laegern 1	4.02	2.08	2.81	1.50	0.54	3.28	3.11	0.33		t
5 Laegern 2	1.51	1.02	1.53	0.92	0.26	2.38	1.24	0.23		t
6 Davos	1.00	0.19	0.28	0.01	0.12	1.02	0.68	0.16		t
7 Konigstein	4.75	1.36	2.81		1.05	1.66	1.45	0.34	0.106	t
8 Grebenau	4.74	1.19	1.66		0.75	1.77	2.46	0.51	0.106	t
9 Witzenhausen	5.78	1.77	2.63		1.19	2.81	2.46	0.44	0.151	t
10 Solling 1	5.03	1.10	3.34	1.21	1.35	2.81	2.41	0.30	0.145	ts
11 Solling 2	8.45	1.43	3.83	1.51	1.82	2.85	3.25	0.43	0.319	ts
12 Heide 1	2.86	0.51	3.61	0.84	1.86	2.42	1.28	0.84	0.050	ts
13 Heide 2	3.60	0.81	4.56	1.03	2.63	1.29	1.74	0.39	0.093	ts
14 Schonbuch 1	2.63	0.47	0.96	0.27	0.35	1.71	1.40	0.19	0.054	t
15 Schonbuch 2	0.88	0.47	0.70	0.37	0.30	1.28	0.88	0.12	0.024	t
16 Feldberg 1	2.77	1.05	3.03	0.41	0.90	1.85	1.38	0.25	0.135	t
17 Feldberg 2	2.11	0.64	1.50	0.46	0.65	2.01	0.95	0.21	0.058	t
18 Wingst	6.16	1.85	14.62	4.32	7.95		2.67	1.43	0.010	ts
19 Harz	4.27						1.98			ts
20 Hils	8.66	2.74	5.25	3.11	3.10		3.36	0.58	0.250	ts
21 Harste	3.13	0.96	1.21	1.25	0.66		2.33	0.34	0.040	ts
22 Spanbeck	5.73	1.28	2.31	1.50	0.79		2.72	0.30	0.110	ts
23 Oberwarmenst. 1	5.45	1.14		1.18		3.62	1.69	0.31	0.120	t
24 Wuelfersreuth	3.33	1.12		0.91		1.72	1.49	0.26	0.054	t
25 Klosterhede	2.80	0.90	18.10	0.89	10.10	2.10	1.04	1.41	0.054	t
26 Tange	2.40	0.53	7.00	1.02	3.90	1.50	0.91	0.59	0.022	t
27 Strodam	2.50	0.87	4.80	1.01	2.50	2.90	1.20	0.55	0.029	t
28 Ulborg 1	1.40	0.59	10.10	0.74	5.70	1.21	0.88	0.74	0.013	t
29 Ulborg 2	2.60	0.83	18.30	1.17	11.30	2.22	1.17	1.45	0.016	t
30 Frederiksborg 1	1.16	0.54	3.10	0.63	1.40	1.32	0.80	0.27	0.013	t
31 Frederiksborg 2	2.49	0.91	6.60	0.95	3.40	3.03	0.95	0.53	0.018	t
32 Aubure	1.95	1.07	2.50	0.46	1.27	2.20	1.30	0.25		t
33 Tillingbourne 1	3.70	0.41	5.57	0.56					0.131	t
34 Tillingbourne 2	3.58	0.38	6.35	0.60					0.164	t
35 Tillingbourne 3	9.61	0.32	14.13	0.52					0.617	t
36 Kilmichael	4.50				4.90	1.06	2.50	0.77		t+s
37 Leanachan	4.90				5.00	2.14	2.60	0.76		t+s
38 Strathyre	4.90				3.50	1.63	2.40	0.57		t+s
39 Kershope	4.00				2.90	1.10	2.80	0.60		t+s
40 Elibank	2.90				3.20	1.30	2.00	0.46		t+s
41 Fetteresso	5.60				6.30	2.86	2.60	0.88		t+s
42 Edinburgh	4.04						1.33	0.68	0.126	t+s
43 Ascot 1	3.37					2.07	3.80	0.48		t+s
44 Ascot 2	3.18					1.84	2.37	0.35		t+s
45 Beddgelert 1	3.98	1.16	23.66	0.70	12.75	1.91	1.30	1.69	0.178	t
46 Beddgelert 2	3.30	0.80	14.72	0.39	8.11	1.51	0.98	1.07	0.195	t
47 Nedstrand	2.06	1.06	18.93	0.40	11.17	1.57	1.27	1.35	0.069	t
48 Winterswijk 1	6.14	0.70	3.61	3.36	1.44	3.89	1.79	0.65	0.013	t+s
49 Winterswijk 2	6.60	0.83	2.84	3.78	1.04	4.41	1.54	0.54		t

- continued -

50 Hackfort	5.32	1.37	5.75	4.38	2.77	4.31	1.76	0.66	0.009	t+s
51 Campina	5.95	1.44		4.81					0.035	t+s
52 Kootwijk	8.41	1.96	8.13	9.77	4.20	2.12	1.54	0.63	0.006	t+s
53 Garderen	3.93	1.16		4.30	2.33	2.08	1.08	0.47		t
54 Zelhem 1	6.15	1.29		6.29	2.94	2.75	1.12	0.55		t
55 Gardsjon	2.51	0.57	8.17	0.42	4.23	1.29	1.02	0.67		t
56 Sodra Vam		0.30		0.28						t
57 Tonnersjo		0.93		0.62						t
58 Ydrefors		1.01		1.32						t
59 Hultasvagen		1.47		0.95					0.135	t
60 Dalanshult	2.57	0.55	2.55	0.32					0.084	t
61 Gungvala	2.62	0.71	1.92	0.78					0.059	t
62 Hjartsjomala	1.71	0.53	1.58	0.33					0.073	t
63 Halaback	2.73	0.61	2.04	0.33					0.082	t
64 Inglatorp	2.50	0.63	1.71	0.48					0.069	t
65 Hammarby	2.22	0.65	1.80	0.68					0.053	t
66 Ryssberget	1.90	0.70	2.15	0.77					0.025	t
67 Gammelstorp	1.81	0.48	1.27	0.43					0.032	t
68 Skillingsmala	2.37	0.61	2.04	0.36					0.074	t
69 Kallgardsmala	2.11	0.36	1.42	0.35					0.055	t
70 Sostared	1.31	0.60	4.96	0.39					0.083	t
71 Fossared	2.91	0.82	7.68	0.56					0.113	t
72 Branhult	2.45	0.75	7.69	0.36					0.109	t
73 Mashult	1.41	0.55	4.41	0.35					0.078	t
74 Normanstorp	2.29	0.33	3.32	0.18					0.110	t
75 Marback	2.24	0.77	5.14	0.53					0.096	t
76 Margreteberg	3.39	1.06	9.19	1.04					0.113	t
77 Ahla	2.09	0.69	4.77	0.84					0.054	t
78 Svarvareskogen	2.24	0.77	8.23	0.49					0.098	t
79 Farda	1.83	0.22	2.59	0.12					0.086	t
80 Lidhult	1.73	0.54	3.69	0.28					0.070	t
81 Orberg	2.28	0.20	1.96	0.14					0.070	t
82 Beteras	3.33	0.42	3.62	0.20					0.094	t
83 Eneryda	1.20	0.31	1.98	0.23					0.026	t
84 Osaby	1.75	0.35	1.57	0.21					0.050	t
85 Krokshult	3.15	0.64	2.30	0.33					0.091	t
86 Knapanas	1.52	0.28	1.16	0.19					0.035	t
87 Notteback	0.97	0.22	1.02	0.15					0.040	t
88 Godeshult	1.26	0.29	1.00	0.15					0.048	t

t=only throughfall is sampled

t+s=both canopy throughfall and stemflow are given

ts=canopy throughfall and stemflow are given as a sum

7.2 Regional variations in throughfall of sulphur and nitrogen over Europe

Within Europe there exist large differences in bulk precipitation and stand precipitation (Table 9 and 10 and Figures 12,13,14). The amount of sulphur found in stand precipitation was significantly greater than in bulk precipitation (Fig. 15), indicating that forests collect atmospheric sulphur much more efficiently than bulk collectors. Bulk precipitation of non sea-salt S-SO_4 varies between 0.28 and 2.69 g $m^{-2}yr^{-1}$. Stand precipitation of S-SO_4 varies between 0.85 and 8.95 g $m^{-2}yr^{-1}$. The ratio between stand precipitation and bulk precipitation and its variation over Europe can be seen in figure 16a and b.

Figure 15. Throughfall and stemflow of sulphur in relation to bulk precipitation of sulphur (g S $m^{-2}year^{-1}$). The European dataset.

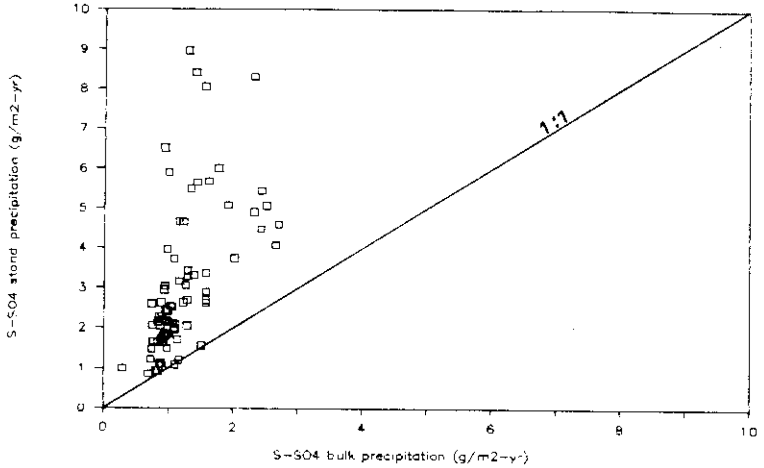


Figure 16 Ratio between stand and bulk precipitation over Europe.

Figure 16a. Spruce and fir stands.

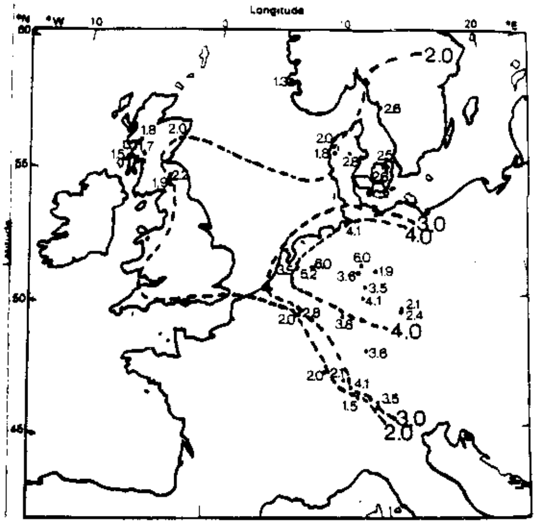
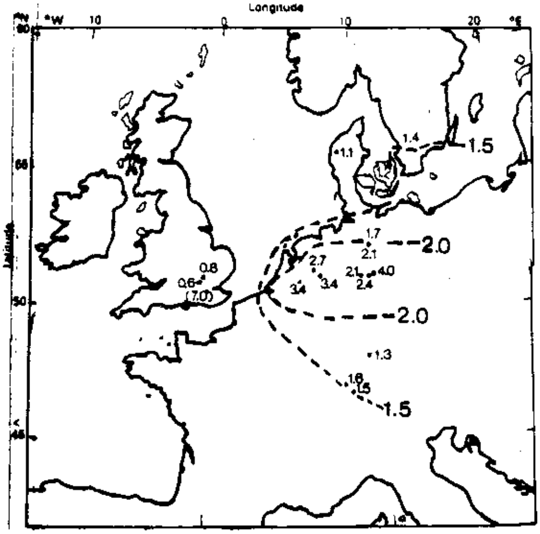


Figure 16b. Pine and deciduous trees.



Bulk precipitation of N-NH_4 varies between 0.29 and 2.17 g m^2yr^{-1} (Fig. 17). Stand precipitation of N-NH_4 varies between 0.01 and 9.77 g $m^{-2}yr^{-1}$. Nitrate nitrogen is less variable: bulk precipitation varying between 0.25 and 1.06 g m^2yr^{-1} and stand precipitation varying between 0.19 and 2.74 g $m^{-2}yr^{-1}$ (Fig. 18). In contrary to sulphur, nitrogen fluxes to bulk collectors exceed the fluxes in stand precipitation at several sites. This probably is caused by irreversible uptake of nitrogen by the canopy.

Figure 17. Throughfall and stemflow of ammonium in relation to bulk precipitation of ammonium (g N $m^{-2}year^{-1}$). The European dataset.

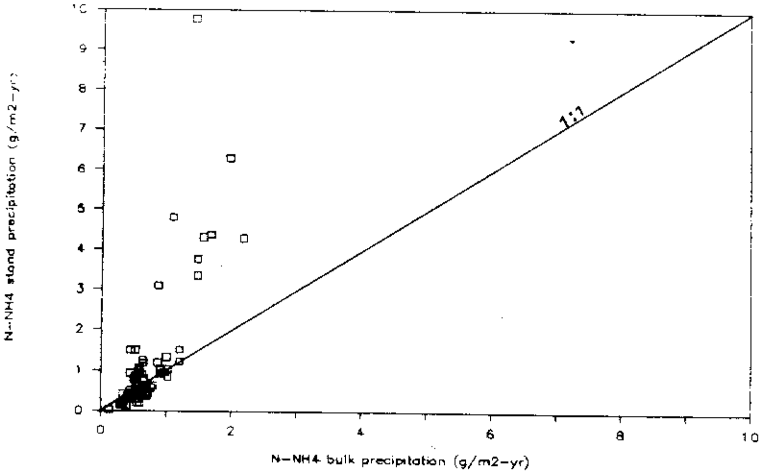
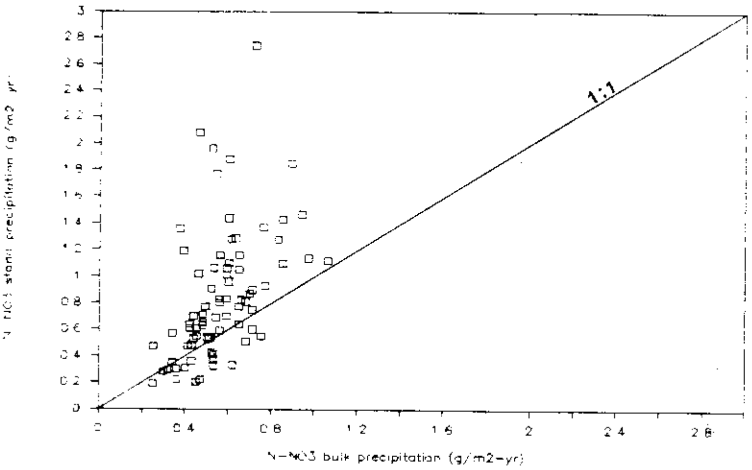


Figure 18. Throughfall and stemflow of nitrate in relation to bulk precipitation of nitrate (g N $m^{-2}year^{-1}$). The European dataset.



Average bulk and stand precipitation fluxes are summarized for 6 European regions in Table 11.

Table 11. Bulk and stand precipitation fluxes of sulphur and nitrogen in 6 broad regions in Europe (g m^{-2} yr^{-1}).

REGION	BULK			STAND			STAND - BULK		
	$S-SO_4$	$N-NO_3$	$N-NH_4$	$S-SO_4$	$N-NO_3$	$N-NH_4$	$S-SO_4$	$N-NO_3$	$N-NH_4$
S-Sweden/ S-Norway	0.96	0.51	0.53	1.96	0.60	0.44	1.00	0.09	-0.09
Denmark	0.88	0.58	0.65	1.73	0.74	0.92	0.85	0.16	0.27
Great Britain	1.87	0.54	0.59	4.17	0.61	0.55	2.30	0.07	-0.04
N-Germany/ Netherlands/ Belgium	1.36	0.64	1.60	5.83	1.36	5.13	4.47	0.72	3.53
C-Germany	1.68	0.70	0.94	5.02	1.28	1.39	3.34	0.58	0.45
S-Germany/ Switzerland/ E-France	0.92	0.50	0.50	2.02	0.92	0.58	1.10	0.42	0.08

$S-SO_4$ is corrected for the contribution of sea-salt.

Relative low amounts of S-SO_4, N-NO_3 and N-NH_4 are found in south Sweden/south Norway. Denmark shows similar S-SO_4 deposition as S-Sweden/S-Norway, but slightly higher nitrogen deposition levels. C-Germany is characterized by both high sulphur and nitrogen loads. Loads of sulphur and nitrogen in S-Germany/Switzerland/E-France are about similar to those in Denmark. In Great Britain sulphur loads are slightly lower than in C-Germany, but nitrogen deposition is about half of the load in C-Germany. The most polluted region is The Netherlands/Belgium/N-Germany, which is characterized by both very high sulphur and nitrogen deposition. In this area the contribution of N-NH_4 to the total nitrogen flux in stand and bulk precipitation is 70 to 80 %, indicating the high ammonia pollution in this region. In the other 5 regions about equal amounts of N-NO_3 and N-NH_4 are deposited.

On the average, stand precipitation minus bulk precipitation is negative for ammonium in Great Britain and Scandinavia, indicating significant N-NH_4 uptake by the tree canopies in these regions. A very important part of the nitrogen input of forested ecosystems all over Europe is in the form of ammonia and ammonium. Therefore much attention should be given to the role of reduced nitrogen components in impact models dealing with nitrogen saturation of ecosystems.

7.3 Basic cation deposition over Europe

Deposition of basic cations in European forests using different approaches, as described in section 4.3, have been calculated by Ivens (in prep.)

Calculation of the mean atmospheric alkaline cation deposition in the studied forests gives clearly different results, depending on the method applied (Table 12). Using present day knowledge, the filtering approach is the best estimate for atmospheric deposition of alkaline cations. The other two approaches show the limits of uncertainty. Calcium is the most important component of the alkaline deposition, accounting for 69% of total alkaline deposition. Magnesium and potassium contribute respectively 8 and 23% to total alkaline deposition. Total median alkaline deposition is ~77 meq m^2yr^{-1}.

Table 12. Bulk precipitation flux (BP), throughfall flux (TF) and calculated atmospheric deposition (AD) of non sea-salt calcium, magnesium and potassium, applying 3 different approaches (meq m^{-2} yr^{-1}).

	calcium		magnesium		potassium	
	median	range	median	range	median	range
BP	29	4- 84	3	0-14	9	0- 73
TF	70	16-206	17	0-60	67	9-212
AD	53	9-254	6	0-58	18	0-201
n	76		68		68	

The annual wet deposition of calcium and magnesium over Europe can be seen in figures 19 and 20. (EMEP data compiled by Pia Antila, Ministry of the Environment, Finland).

Figure 19. Annual wet deposition of calcium at EMEP monitoring stations in 1986.

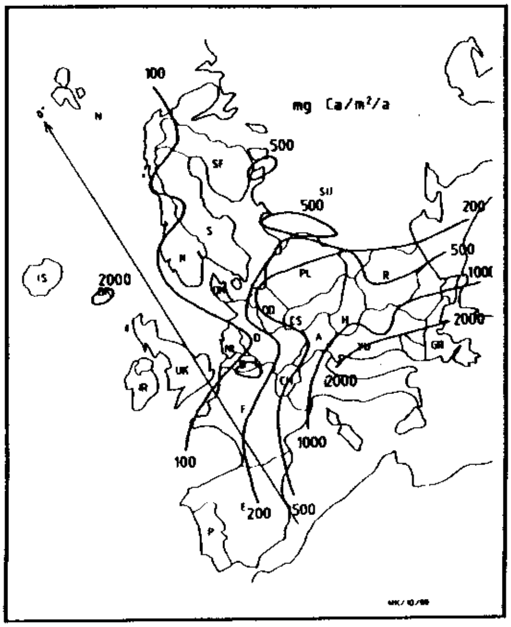
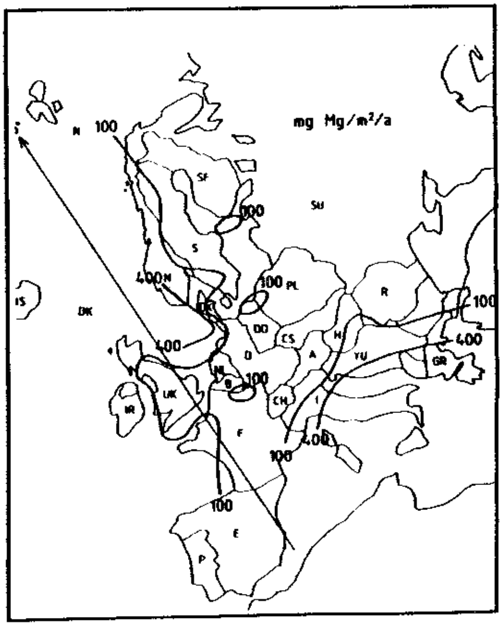


Figure 20. Annual wet deposition of magnesium at EMEP monitoring stations in 1986.



Non sea-salt sources of Ca, Mg and K are: 1) soil dust (mainly from agricultural land); 2) agricultural fertilizers (liming); 3) road dust (mainly from unpaved roads); 4) limestone quarries; 5) fuel burning (generating fly-ash). According to estimates of Gatz et al. (1986) for 31 "eastern" USA-states, open sources (wind erosion, tilling, unpaved roads) generate more than 95% of the total mass of alkaline materials emietted to the atmosphere. Conventional sources (fuel combustion, industrial sources, solid waste disposal and transportation) appeared to be only small contributors to the total emission of alkaline particles in these states.

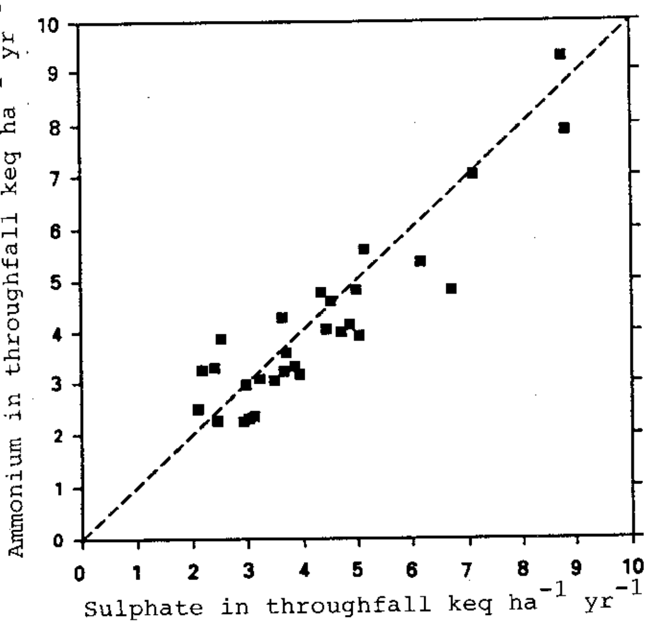
The figures in Table 12 show a wide range. This is probably due to the geographical variability of soil composition and wind-erodibility of soils. In areas where soil and rock consist of calcareous material, relative large alkaline atmospheric inputs to forests will occur. Therefore, median values of table 14 are overestimates of alkaline deposition to forests in areas with non-calcareous soils, which are most treathened by soil acidification.

Alkaline deposition can be an important factor in counteracting acid atmospheric inputs. Ivens et al. (1989b) calculated that in 81% of the forest stands in Europe 20 to 50% of the sulphur induced acid input was neutralized by alkaline, calcium and magnesium deposition.

7.4 Interaction of sulphur and nitrogen

Adema et al. (1986) showed in laboratory experiments that SO_2 deposition to thin water films is enhanced when acids formed in the water are neutralized by NH_3 deposition. Results from Dutch sites (Ivens, 1989c) and Swedish sites (Westling & Lövblad, 1989) confirm these experiments and indicate that near ammonia source areas not only high ammonium inputs to the forest soil occur, but also large sulphur inputs (figure 21). The latter could be due to co-deposition of ammonia and sulphur dioxide onto water films on tree surfaces, but also to deposition of ammonium sulphate particles.

Figure 21. **Sulphate in throughfall versus ammonium in througfall for 29 Dutch sites. (Ivens, 1989c)**



7.5 Comparison between modelled and monitored throughfall deposition

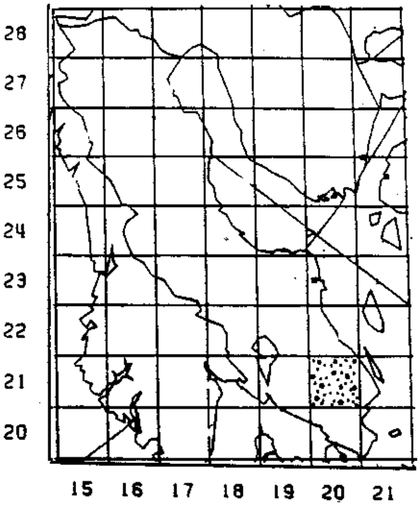
Throughfall data from a monitoring network in southern Sweden show considerably higher sulphur deposition levels than was expected from model calculations. They also indicated larger variations between different forest stands than was expected by the models (Westling).

The EMEP-model predicts a total sulphur deposition of ~1.2 g $Sm^{-2}yr^{-1}$ (= 11.5–12 kg S $ha^{-1}yr^{-1}$) for a grid square in southern Sweden covering only land (Figure 22). For Kronoberg county the throughfall monitoring results are presented in Table 13.

Table 13. Throughfall monitoring in Kronoberg, Sweden.

Tree	Number	1987	1988
species	of plots	mean (S.D.)	mean (S.D.)
spruce	6	20.2 (8.7)	23.8 (7.69)
pine	3	11.5 (2.7)	14.8 (3.5)
deciduous	0	-	-
bulk precip.	9	8.3 (1.7)	10.2 (1.8)

Figure 22. The EMEP grid over Sweden. Grid square containing Kronobergs län is dotted.



The same has been demonstrated in The Netherlands (Ivens, 1989c). In The Netherlands sulphur and ammonium throughfall deposition appears to exceed model results by a factor 2 (Table 14). Moreover, calculated atmospheric nitrogen (both ammonium and nitrate) deposition showed to correlate poorly with throughfall deposition.

Table 14. Mean calculated (model) and observed throughfall deposition (eq $ha^{-1}yr^{-1}$) of 29 forest sites in The Netherlands and the correlation coefficient (r) between calculated and observed deposition. (From Ivens, 1989b)

	model [1]	throughfall [2]	r
	mean (S.D.)	mean (S.D.)	
SO_x	2150 (330)	4090 (1640)	0.56
NH_x	2080 (590)	4270 (1740)	0.00
NO_x	1570 (90)	970 (30)	0.17

[1] derived from RIVM, 1988

[2] SOx corrected for sea-salt contribution

Measurements of sulphur and nitrogen stand precipitation have been compared with model estimates (Ivens et al., 1989b; Ivens et al., 1989d). The model estimates were calculated with the RAINS/EMEP model of the International Institute for Applied System Analysis (Laxenburg/Austria), (Alcamo et al., 1987; Alcamo & Bartnicki, 1988). The data set that was used for this comparison was slightly different from the one described in this appendix, e.g. the Swedish data set had not been incorporated by then.

Sulphur

The RAINS/EMEP model predicted deposition onto deciduous forests very well, without significant bias (Fig. 23). The ratio between calculated and observed values was 1.0 ± 0.3, calculated fluxes being not significantly different from the throughfall fluxes. The coefficient of determination (r^2) between observations and model estimates was 0.76.

The model underestimated deposition onto coniferous stands (Fig. 24). The observed throughfall fluxes at these stands were 1.6±0.8 times greater than the model estimates; the difference between calculated and observed values was statistically significant. The coefficient of determination (r^2) between calculations and observations was 0.43. As the RAINS/EMEP model underestimates S-deposition onto coniferous stands, correction coefficients may be needed to assess the deposition onto areas where conifers are the main tree species.

Figure 23. Model estimate of sulphur deposition versus throughfall and stemflow of sulphur in deciduous stands (Ivens et al., 1989b).

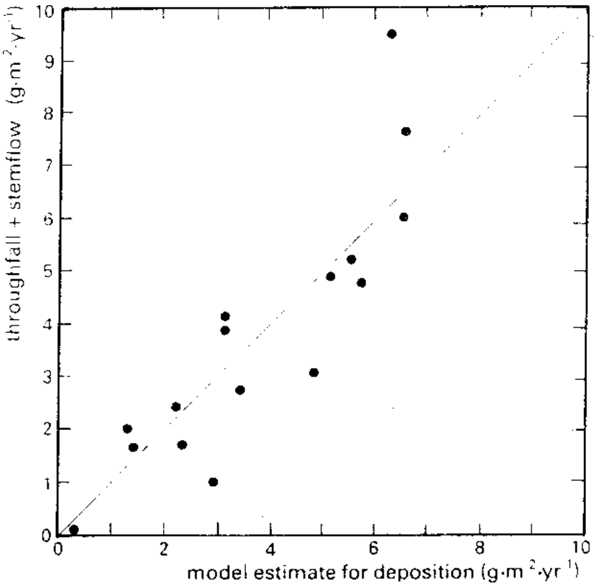
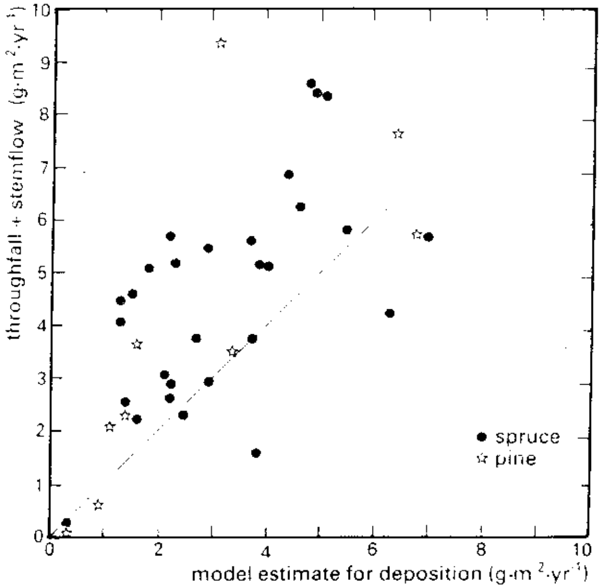


Figure 24. Model estimates of sulphur deposition versus throughfall and stemflow of sulphur in coniferous stands (Ivens et al.,1989b).



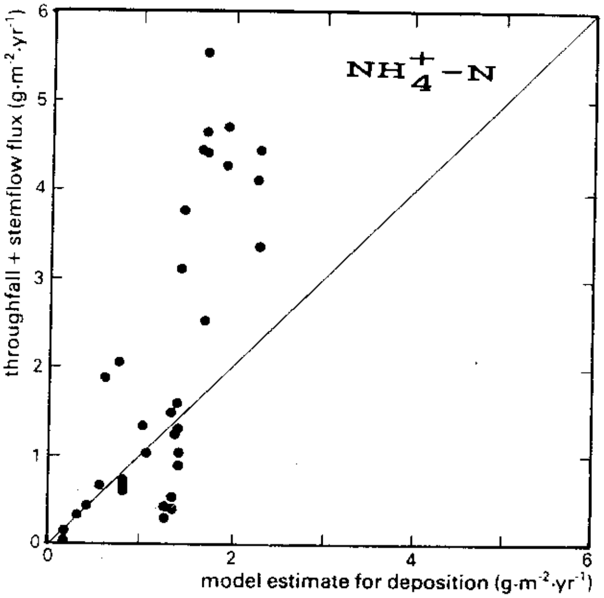
Nitrogen

Throughfall of N-NH_4 appeared to be on an average 1.7±1.5 times greater than model estimates (Fig. 25). The difference between observed and calculated deposition was significant. The coefficient of determination was 0.35. In particular at sites in N-NH_4 polluted areas model predictions are much too low. This probably is due to the big influence of dry deposition of NH_3 in such sites.

On the average there was no significant difference between observations and model estimates for N-NO_3 deposition (Fig. 26). The ratio between observations and calculations was 1.0±0.6 for N-NO_3. The coefficient of determination between calculations and observations was 0.42.

Figure 25.

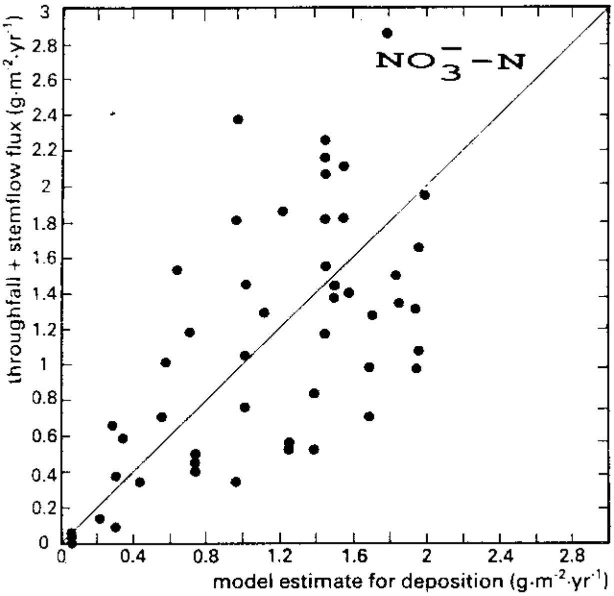
Model estimate of ammonium deposition versus throughfall and stemflow of ammonium (Ivens et al.,1989c)



It has to be emphasized that throughfall fluxes might be underestimates of the total atmospheric nitrogen deposition, because of irreversible assimilation of nitrogen by the canopy. Therefore, we expected both N-NH_4 and N-NO_3 calculations to exceed throughfall measurements. Because this is clearly not the case in figures 25 and 26, either this canopy absorption was not significant in these measurements or dry deposition is relatively great.

Figure 26.

Model estimate of nitrate deposition versus throughfall and stemflow of nitrate (Ivens et al., 1989c)



7.6 Relationship between forest type and throughfall deposition

The ratio of stand precipitation to bulk precipitation (SP/BP) can be used as a measure for the filtering efficiency of forests. The SP/BP ratio appears to be very variable. Nevertheless, it appears from this data set that filtering of sulphur compounds by spruce and fir forests is somewhat more effficient than by pine and deciduous forests (Table 15).

Table 15. Sulphur filtering efficiency, expressed as the ratio of stand precipitation (SP) to bulk precipitation (BP), of different kinds of forests (standard deviation in brackets)

European data set

FOREST TYPE:	SPRUCE + FIR	PINE	DECIDUOUS
SP/BP	2.7 (1.0)	2.1 (1.8)	2.1 (0.8)
n	52	9	15

Swedish data set

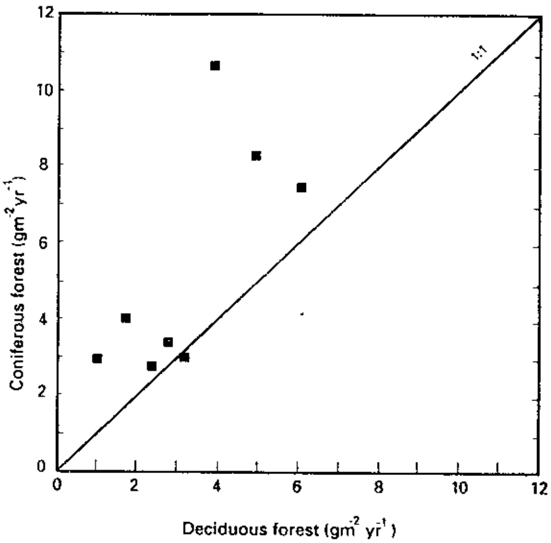
FOREST TYPE:	SPRUCE	PINE + DECIDUOUS
SP/BP	2.3 (0.4)	1.5 (0.3)
n	20	7

A better comparison of the stand precipitation deposition in different kinds of forests can be done for sites where stand precipitation is measured in several different forests simultaneously. In our European data set such a comparison is only possible for eight sites. At seven sites stand precipitation is greater in coniferous forest than in deciduous forest (Fig. 27). The average ratio of stand precipitation in coniferous stands and stand precipitation in deciduous stands at these eight sites is 1.8 (±0.8), indicating that coniferous stands are almost twice as efficient filters of sulphur as deciduous forests.

The Swedish data set contains contemporary data. The average ratio of throughfall deposition to bulk precipitation for spruce is 2.3 and for pine and deciduous 1.5. The standard deviation is considerably less than for the European data set, 0.4 and 0.3, respectively.

Figure 27.

Sulphur flux onto the forest floor in coniferous stands versus sulphur flux in deciduous stands.



7.7 Relationship between throughfall deposition, forest structure and site characteristics

The local variations observed in the Swedish network have to a major extent been related to the forest structure.

In the Gårdsjö study, sulphur transports in lake subcatchments indicated that a coniferous forest stand will collect approximately 3 times the amount of sulphur as will a clear cut area (Figure 28, data from the Gårdsjö study).

The Swedish throughfall data set seems to confirm the fact that spruce stand collect more dry deposition than pine and deciduous stands, though the monitoring is predominantly carried out in Norwegian spruce stands. Only 9 of the 36 plots are pine and deciduous forests (Figure 29).

Tree species seem to be the most important factor for differences in deposition.

Age and height of the trees seem to be less important or do in a complex way affect the filtering capacity. In figures 30 and 31 the dry deposition is plotted versus tree age and tree height for all sampling plots of the Swedish data set. There is no better correlation if only spruce stands are considered (Figures 32 and 33).

However, when variations in air pollution load and exposure are minimized, as is the case when monitoring in the same area, a relation between dry deposition and stand age is observed. The stand age is in turn correlated to size and density of the trees (Figures 34 and 35).

Figure 28. Sulphur transport (kg S·ha^{-1}year^{-1}) from terrestrial parts catchments within the Gårdsjö area in relation to coniferous forest cover (%).(Hultberg & Grennfelt 1986).

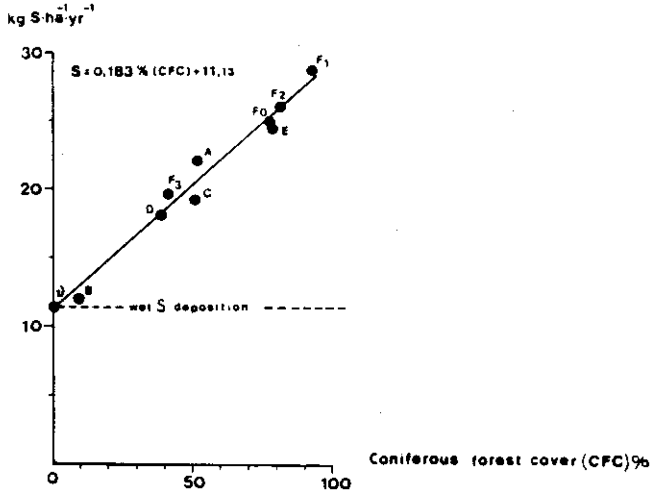


Figure 29. Dry deposition of sulphur (kg S ha^{-1} year^{-1}) for different tree species. The Swedish dataset 1988.
1=spruce 2=pine 3=deciduous

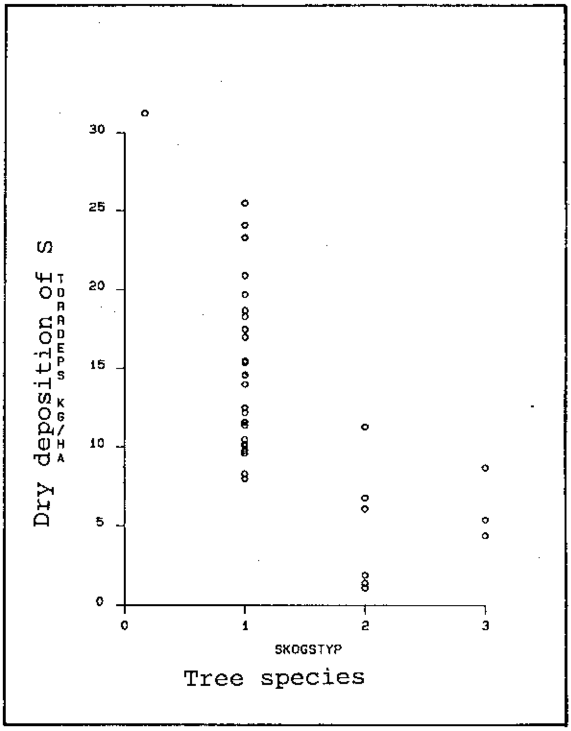


Figure 30. Dry deposition of sulphur (kg S ha^{-1} year^{-1}) in relation to tree height (m). The Swedish dataset 1988.

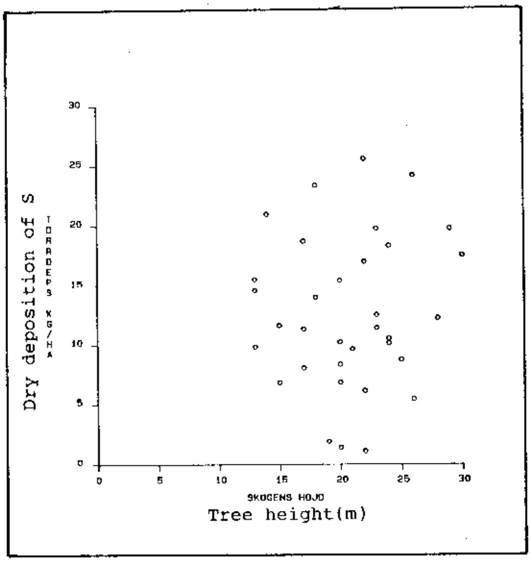


Figure 31. Dry depositionof sulphur (kg S ha^{-1} year^{-1}) in relation to forest age (years). The Swedish dataset 1988.

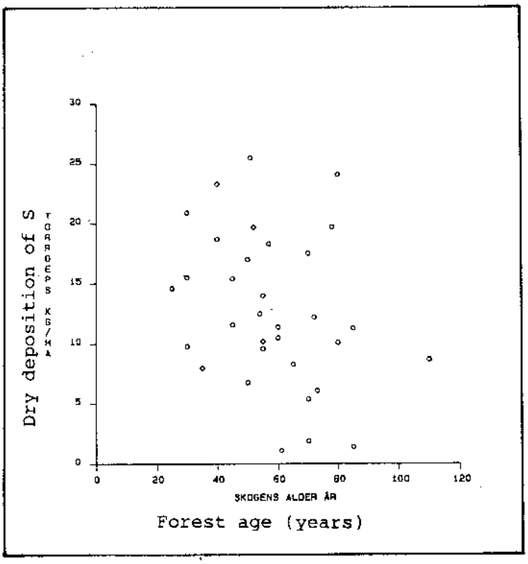


Figure 32. Dry deposition of sulphur (kg S $ha^{-1}year^{-1}$) to spruce stands in relation to tree height (m). The Swedish dataset 1988.

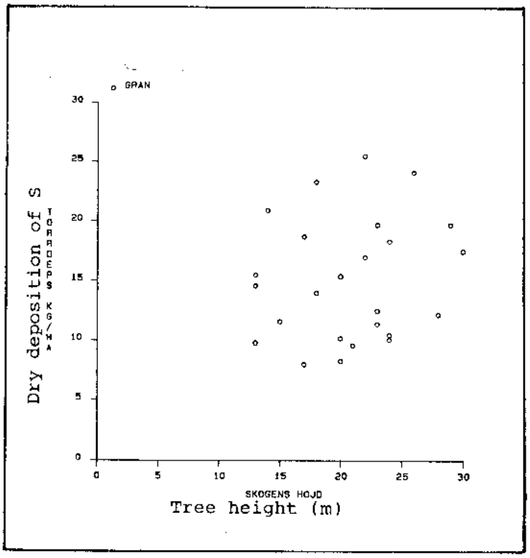


Figure 33. Dry deposition of sulphur (kg S ha^{-1} $year^{-1}$) to spruce stands in relation to tree age (years). The Swedish dataset 1988.

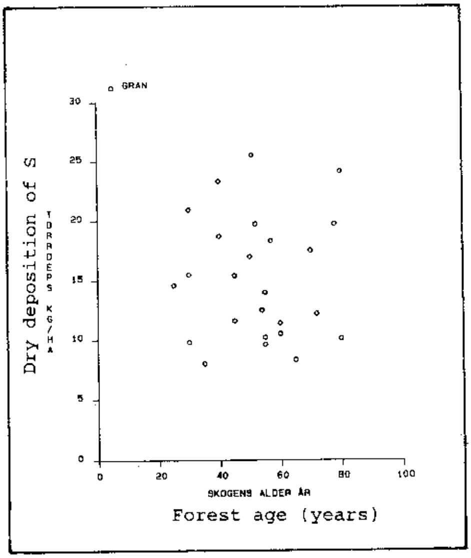
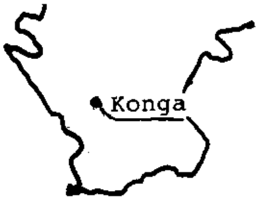


Figure 34. Excess sulphur in throughfall at Konga, Sweden 1984-85.
The black bar is bulk precipitation
The black+white bar is throughfall



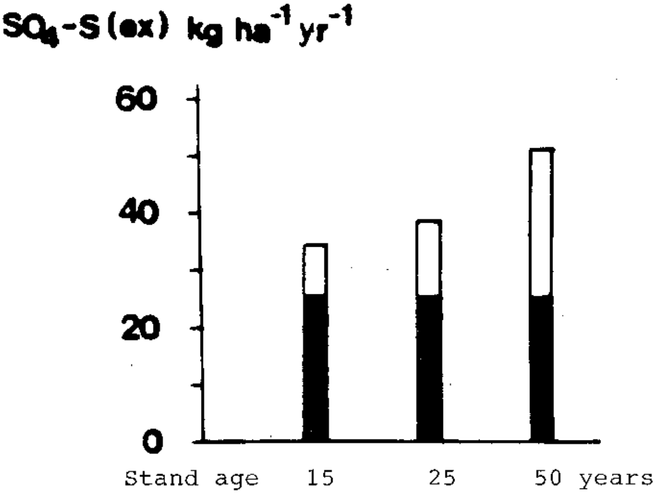
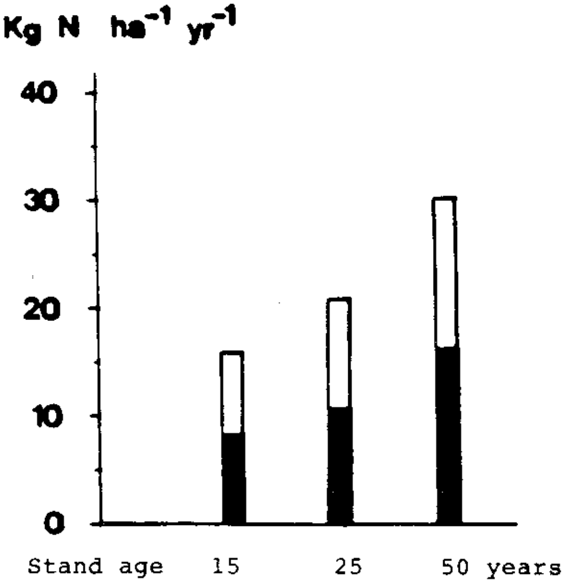
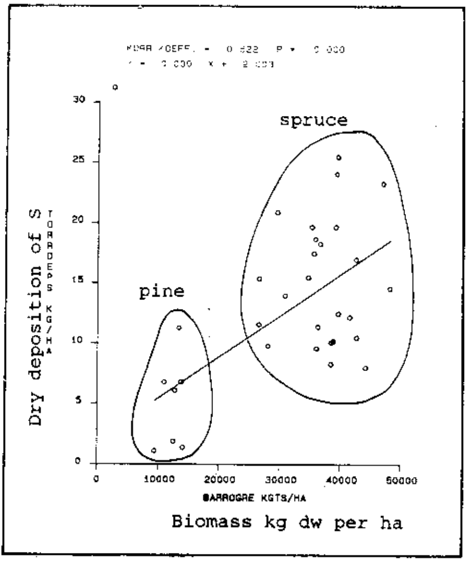


Figure 35. Nitrate and ammonium in throughfall at Konga, Sweden 1984-85.
The black bar is NH_4^+, the white bar is NO_3^-



The biomass for conifers as amount of needles and branches were calculated out of relatively simple forest characteristics in accordance to a procedure by Marklund (1987). We found the biomass to correlate fairly well with the dry deposition. However, two groups of data appear in the diagram. The pine stands and the spruce stands are well separated (Figure 36).

Figure 36. Dry deposition of sulphur (kg S $ha^{-1}year^{-1}$) in relation to biomass (needles and branches) of coniferous stands (kg dry weight per ha). The Swedish dataset 1988.



If biomass (as needles and branches) is a good measure of the filtering capacity of the tree stand a still better correlation should be expected. Our estimation of biomass is however rather simple. It is possible that a better correlation can be obtained if this estimation is made in a more sophisticated way. The biomass is related to the total forest stand (per ha). We have tried to relate it to the individual trees by dividing with the number of trunks per ha (Fig. 37a) and with the height (Fig. 37b). However, this does not increase the correlation.

Figure 37 a. Dry deposition of sulphur (kg S ha^{-1}year^{-1}) in relation to biomass (needles and branches) per tree in coniferous stands (kg dry weight per tree). The Swedish dataset 1988.

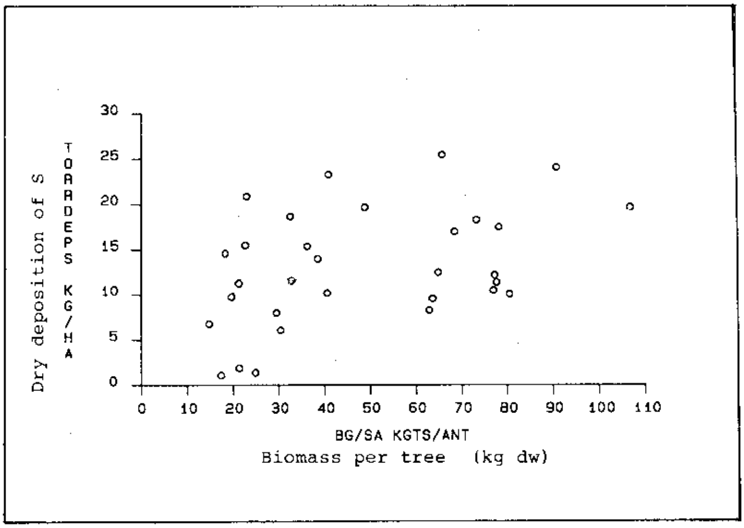
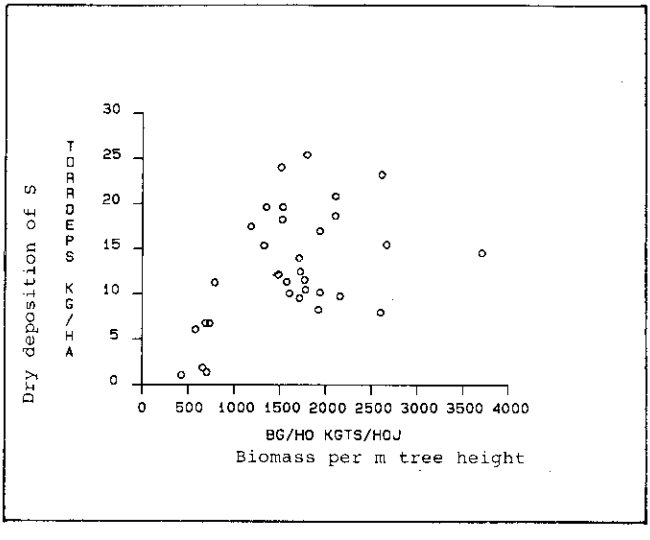


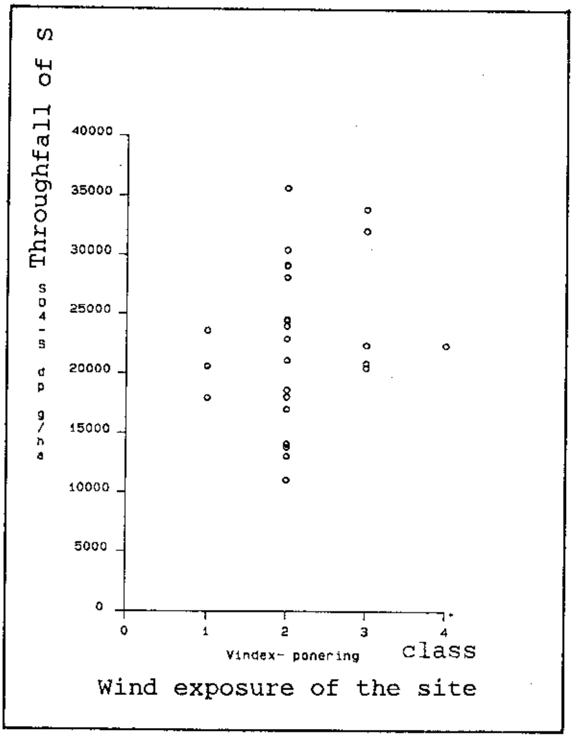
Figure 37 b. Dry deposition of Sulphur (kg S ha^{-1}year^{-1}) in relation to biomass (needles and branches) per m tree height in coniferous stands (kg dry weight per m)



Site characteristics like altitude show no relation to dry deposition. There seems, however, to be an effect on dry deposition due to wind exposure of the site. The comparison is complicated by the fact that most of the sites are relatively shielded. Only six sites are very exposed (Figure 38).

Figure 38.

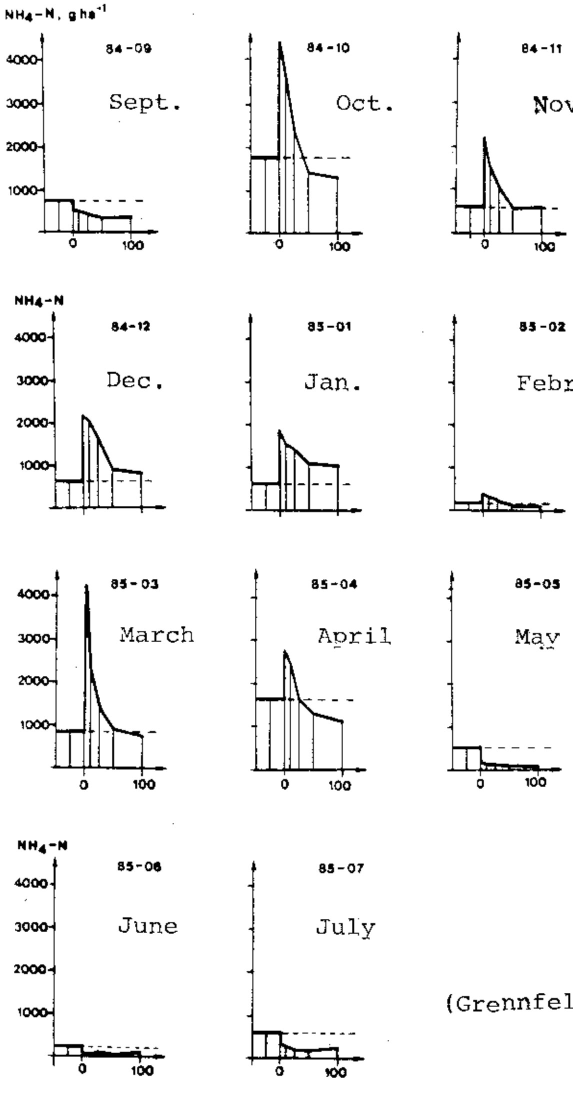
Throughfall deposition of sulphur (kg S $ha^{-1}year^{-1}$) in relation to wind exposure class of the site.
1= shielded 4=very wind exposed. The Swedish dataset 1988.



7.8 Differences between bulk precipitation and throughfall deposition of nitrogen

At most sites in Sweden the throughfall of ammonium is less than the deposition with bulk precipitation. At several sites this is also the case for nitrate (figures 10 and 11).
However, there is a seasonal variation indicating that total deposition of nitrate and also ammonium can be estimated via throughfall monitoring during winter conditions, when the trees are less active (Grennfelt & Hasselrot; figure 39, and IVL-data; figure 40a-b).

Figure 39. Monthly variation of NH_4^+ in bulk precipitation and throughfall at a coniferous forest edge, September 1984 to July 1985 at Tönnersjö, Sweden.

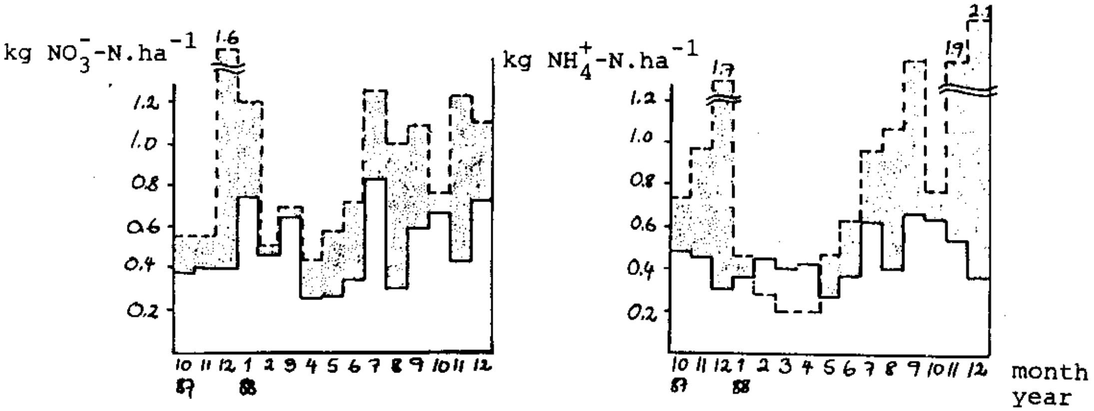


(Grennfelt & Hasselrot 1987)

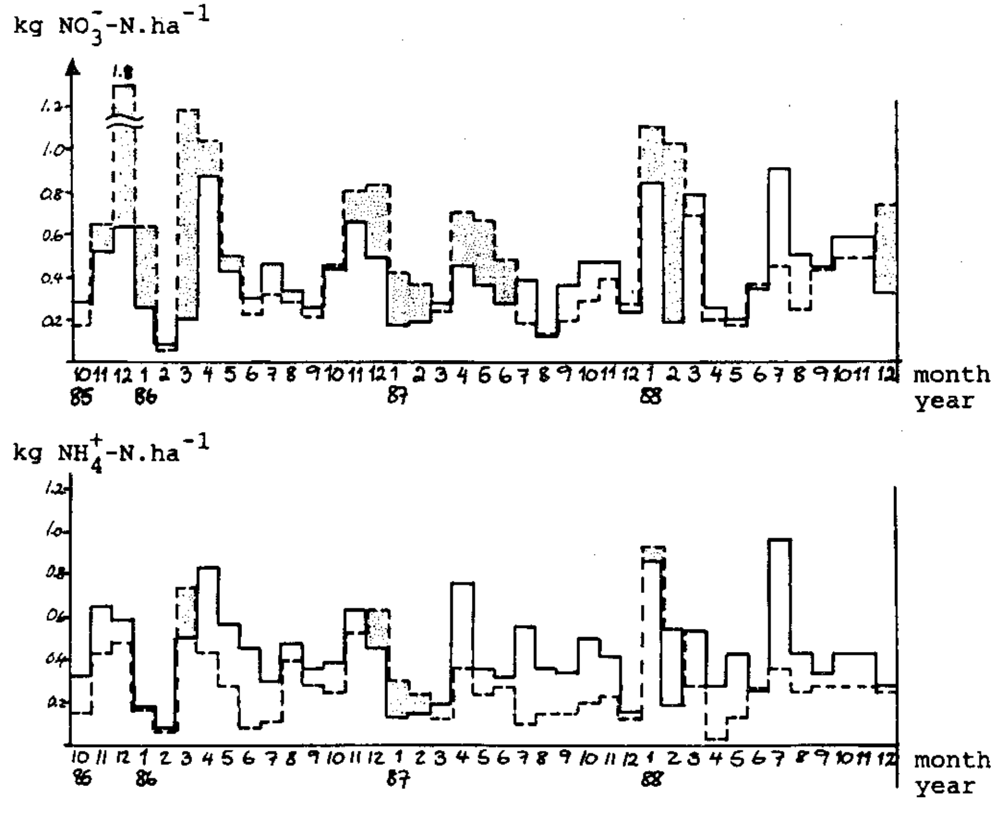
Figure 40. Monthly variations in throughfall of nitrogen in southern Sweden. Swedish dataset

—— bulk deposition
---- throughfall
In the shadowed areas throughfall>bulk deposition

a.Monitoring data from Halland (Ahla) 1987-88



b.Monitoring data from Blekinge (Dalanshult) 1985-88

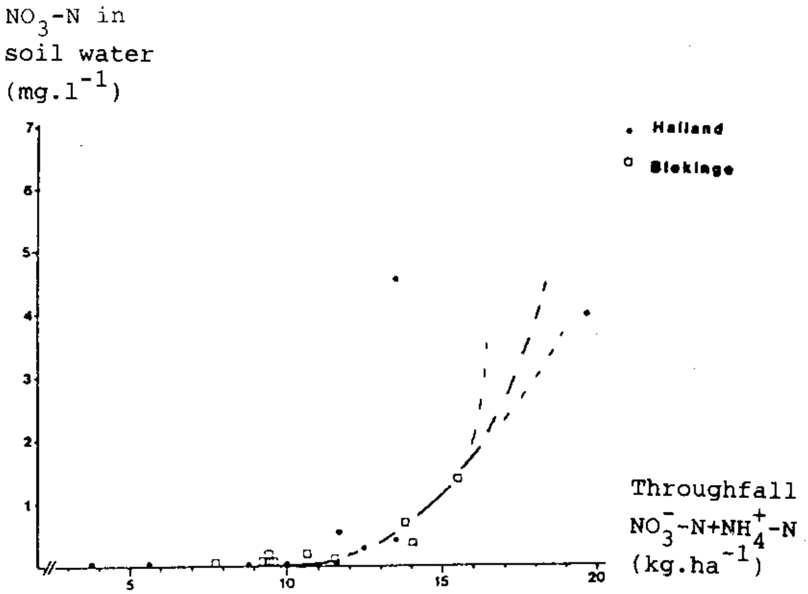


The difference between inorganic nitrogen fluxes in throughfall and bulk precipitation will depend on both the magnitude of dry and droplet deposition to the forest and the net canopy uptake. Bulk precipitation fluxes of nitrogen only exceed throughfall fluxes in areas remote from large anthropogenic nitrogen emissions. In these remote areas dry deposition to forest is expected to be relatively low. In nitrogen polluted areas, dry deposition of nitrogen to forests will be relatively high and, despite irreversible foliar uptake of nitrogen, the throughfall flux will exceed the bulk precipitation flux. Foliar nitrogen uptake presumably depends on the nitrogen status of the forested ecosystems. Nitrogen canopy uptake will be more in nitrogen deficient systems. This could not be verified, because no sufficient data on the nitrogen status of the forests were available in the present data set.

7.9 Relationship between throughfall deposition of nitrogen and nitrate in soil water

The Swedish throughfall data for nitrogen show a relation to nitrate concentration in soil water (50 cm deep, below the root-zone, in most cases in the lower part of the B-horizon (figure 41), (Westling 1989).

Figure 41. Relation between throughfall deposition of nitrogen (nitrate and ammonium) and nitrate in soil water. Westling 1989.



This indicates that also in more remote areas nitrogen in throughfall can be used to detect high levels of nitrogen deposition.

8. CONCLUSIONS

The evaluation of throughfall data shows the advantages and disadvantages of the throughfall monitoring technique.

Throughfall data for sulphur can be used directly to estimate the total deposition to a forest ecosystem. In fact, throughfall is the only realistic alternative for determination of the actual deposition to aerodynamically complex terrain, such as forests in general and forest edges in particular. The method can be used in most areas in Europe. Only in very remote, little polluted areas, will the internal cycling of sulphur in vegetation be of significance in relation to the total sulphur fluxes (up to 20%).

Throughfall monitoring data show that there are large variations in sulphur deposition on the local scale.

The local variations are mainly due to variations in wind exposure of the site and in filtering capacity of the forest.

Spruce and fir trees have a larger filtering biomass than other trees, and have been found to collect almost twice the amount collected by pine and deciduous trees. In this work, it has not been possible to find the perfect correlation between deposition and simple forest and site characteristics. They seem to interact in a complex way. Air turbulence around the site during the measurement period or surface roughness of the site, for example, are parameters which are difficult to determine but would probably correlate well with the throughfall results. Access to such parameters would also be useful for modelling work.

Large-scale variations over Europe are to a great extent due to differences in air pollution load. There is a larger throughfall deposition in Central Europe than in Scandinavia, for example.

Throughfall monitoring data for nitrogen cannot be used directly to estimate the total nitrogen deposition, due to the internal cycling of nitrogen in vegetation. Assuming that canopy exchange of nitrogen is an irreversible net uptake, throughfall fluxes of nitrogen will give too low an estimate. Only in areas such as The Netherlands, where there is high deposition of nitrogen, and thus reduced importance of canopy uptake, is it possible to use the throughfall data for deposition estimates.

In some areas it seems possible to use the winter throughfall data to estimate the total deposition during the cold period when there is low biological activity.

Due to the fact that canopy uptake seems to be the normal condition, high levels of nitrogen in the throughfall indicate that the atmospheric deposition may be severe to the forest. In southern Sweden throughfall data can be used to detect areas with a high nitrogen load and areas where there is a risk of nitrate leaching to soil water.

Throughfall data for sulphur and ammonium indicate that in proximity to ammonia source areas not only large ammonium inputs to the forest soil occur, but also large sulphur inputs, indicating a co-deposition of ammonia and sulphur dioxide.

As for nitrogen, throughfall data cannot be used directly for estimating the total base cation deposition, due to the internal cycling of base cations in vegetation. Using present day knowledge, the best estimate can probably be made using throughfall and bulk precipitation data for sodium and making a "filtering" analogy using bulk precipitation data for the other ions.

In our experience, throughfall data on base cations are also useful from another point of view: they provide valuable information on the leakage of base cations and thus on the internal flux of nutrients and its relation to the acid deposition and soil status.

As a general conclusion, throughfall data are very valuable for estimating deposition and for producing information about the status of the forest. They can be used separately or in combination with model data. Model data alone cannot give this information.

Even more information could be achieved from throughfall measurements:

- if data were available from different regions all over Europe,
- if these data were comparable as regards monitoring periods and techniques,
- if these data were combined with information not only on air pollution, but also on site and forest characteristics.

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