CONVENTION ON LONG-RANGE TRANSBOUNDARY AIR POLLUTION
International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests
International Co-operative Programme on Integrated Monitoring

United Nations
Economic Commission
for Europe

Cause-effect Relationships of Forest Ecosystems

Joint report by ICP Forests and ICP Integrated Monitoring

Federal Research Centre for Forestry and Forest Products (BFH)

Finnish Environment Institute (SYKE)

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Preface

For more than 20 years the Convention on Long-range Transboundary Air Pollution (CLRTAP) has been striving to control air pollutant emission in Europe and North America. Its Working Group on Effects (WGE) has been responsible for the scientific underpinning. The International Cooperative Programmes (ICPs) identify air pollution effects on the environment through monitoring, modelling and scientific review. The scientific network of the ICPs and the monitoring and modelling results have been promoting the development of the Convention and are an essential component for its success in the future.

The International Cooperative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) collects in close cooperation with the European Commission data and determines cause effect relationships of changes in forests due to air pollution and other stresses by means of monitoring both at the large scale and at the scale of ecosystems. The International Cooperative Programme on Integrated Monitoring of Air Pollution Effects on Ecosystems (ICP IM) determines and predicts the state of ecosystems or catchments and their changes from a long-term perspective with respect to the regional variation and impact of air pollutants.

Both ICPs have been co-operating closely for a number of years now although the objects under study are different at first sight. ICP IM is focusing on catchments in undisturbed ecosystems while ICP Forests monitors forest ecosystems which are managed regularly. As most ICP IM sites are within forest areas and as many countries have linked their plots of both programmes within one monitoring system, it is common agreement to intensify the co-operation. One result of this intensive co-operation is the harmonisation of assessment methods. As the next level of cooperation, this report reviews the outstanding data and information gathered by both programmes and presents for various areas of research the main findings. In addition results and information were contributed by a large number of participating countries. All support received from the countries in the preparation of the report is gratefully acknowledged.

It is expected that this report will intensify the co-operation between the National Focal Centres (NFCs) in all participating countries and help to intensify the work in those areas which will be of highest priority for the two programmes in future.

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1 Introduction

Aim of this report

Forests are subject to a large number of natural and anthropogenic influences. Among the anthropogenic influences, long-range transboundary air pollution has been of major concern for more than two decades. The understanding of the role of air pollution and other factors requires the understanding of the complex cause-effect relationships existing in forest ecosystems.

It is the aim of this report to inform on cause-effect relationships assessed by ICP Forests and ICP IM. In line with the mandates of the two programmes the report emphasizes effects caused by air pollution (such as acidification, eutrophication and damage by toxic elements), but refers also to climate change and other factors. Moreover, the report identifies overlap and gaps in knowledge in the two ICPs and presents an outlook on the future cooperation of the two programmes.

Activities of ICP Integrated Monitoring

The activities of ICP IM started in the mid 1980s as a joint Nordic co-operation programme under the Nordic Council of Ministers. From 1989 to 1991 it was run as a pilot programme under the CLRTAP, and became a permanent ICP in 1993. The main objectives of the ICP IM are:

– Monitoring of the biological, chemical and physical state of ecosystems (catchments/plots) over time in order to provide an explanation of changes in terms of causative environmental factors, including natural changes, air pollution and climate change, with the aim to provide a scientific basis for emission control;
– Development and validation of models for the simulation of ecosystem responses in order to (a) estimate responses to actual or predicted changes in pollution stress, and (b) make regional assessments in concert with survey data;
– Biomonitoring to detect natural changes, in particular to assess effects of air pollutants and climate change.

The full implementation of the ICP IM will allow determining ecological effects of heavy metals, persistent organic substances and tropospheric ozone. A primary concern is the provision of scientific and statistically reliable data that can be used in modelling and decision making. The ICP IM sites (mostly forested catchments) are located in undisturbed areas, such as natural parks or comparable areas. The ICP IM network presently covers about 50 sites, with on-going data submission, in 21 countries.

Activities of ICP Forests

ICP Forests was established under CLRTAP in 1986. In 1987 the European Commission (EC) also started to monitor forest condition in the EU-Member States. However, ICP Forests and EC merged their previously two monitoring programmes into a joint one in 1991. Since then both have been monitoring forest condition and publishing their results jointly. Consequently most of the activities of ICP Forests mentioned in this report are carried out in close co-operation with the EC. ICP Forests pursues the following mandate:

– To monitor effects of anthropogenic stress factors (in particular air pollution) and natural stress factors on the condition and development of forest ecosystems in Europe;
– To contribute to a better understanding of cause-effect relationships in forest ecosystem functioning in various parts of Europe.

For each part of the mandate ICP Forests has implemented a separate monitoring intensity level. At Level I the large scale variation of forest condition is assessed by means of an extensive survey on more than 6000 plots. At Level II intensive monitoring is carried out on 860 plots in 30 countries in order to trace in detail the influence of specific stress factors in main forest ecosystems. On these plots a larger number of key factors are measured. Apart from air pollution, ICP Forests has widened the scope of its programme to the topics of biodiversity and climate change. In view of these topics, the major objectives of the intensive monitoring at Level II are in particular the assessment of:

- Responses of forest ecosystems to air pollution and its changes;
- Differences between present loads and critical loads of atmospheric deposition (tolerable long-term inputs in order to protect the sustainability of the ecosystems);
- Impacts of atmospheric deposition on the ecosystem condition according to scenario analyses;
- Changes in carbon storage in forests (net carbon sequestration);
- Changes in indicators related to the various functions of forest ecosystems to assess its long-term sustainability.

Both parts of the programme – extensive monitoring on Level I and intensive monitoring on Level II – yield the potential to transfer process information, gained on the plot-level (Level II) to the European scale (Level I). The methods for the assessment of the chemical, physical and biological parameters are harmonised throughout both ICPs and are laid down in two manuals. More information on the programmes is available on the web sites of ICP Forests (www.icp-forests.org) and ICP IM (www.vyh.fi/eng/intcoop/projects/icp_im/im.htm).

Contents of the report

An overview of the monitoring approaches of the two ICPs is given in Chapter 2, along with an assessment of overlap and gaps in knowledge. Chapter 3 presents results of relevance for cause-effect research, emphasising the relationship between crown condition and species composition of the ground vegetation with environmental factors, the response of the ground vegetation, the sequestration of carbon in forest ecosystems, the toxic effects of heavy metal depositions and the acidifying and eutrophying effects of atmospheric deposition on soil, soil solution and surface water chemistry. These results were achieved by means of the Level II approach of ICP Forests and the integrated monitoring approach of ICP IM in the forests of this programme's plots and catchments. Chapter 4 provides an outlook, including ideas on the future co-operation of ICP Forests and ICP IM.

2 Monitoring activities

2.1 Information at ICP Forests Level II and ICP Integrated Monitoring

Information on the surveys carried out at ICP Forests Level II and by ICP Integrated Monitoring is presented in Table 1. Surveys carried out in both programmes are crown condition, foliar condition, species composition of the ground vegetation, soil chemistry, soil solution chemistry, tree growth, atmospheric deposition, meteorology, phenology and litterfall. Surveys that are carried out at the ICP Forests Level II only are ozone injury and remote sensing, whereas soil biology, surface water chemistry and bird inventories are assessed only by ICP Integrated Monitoring. The locations of both the plots of ICP IM and the Level II plots of ICP Forests are mapped in Figure 1.

Table 1: Surveys carried out at ICP Forests Level II and ICP Integrated Monitoring on forest plots and all plots (F/All)

Surveys conducted	ICP Forests Level II			ICP Integrated Monitoring		
	periodicy	intensity	Plots	periodicy	Intensity	F/All
Atmospheric deposition: (bulk deposition, throughfall, stemflow)	Weekly – monthly	Part of the plots	496	Weekly – monthly	Part of the sites (bulk deposition all)	43/51
Ambient air quality	Daily-weekly	Part of the plots	79	Daily-weekly	Part of the sites	36/42
Ozone injury	Yearly	Part of the plots	79			
Meteorological condition	Daily	Part of the plots	201	Daily	Part of the sites	35/42
Crown condition	Yearly	All plots	862	Yearly	Part of the sites	31
Foliar chemistry	Every 2 years	All plots	855	Yearly	Part of the sites	32
Litterfall (chemistry)[1]	Yearly	Part of the plots	350	Yearly	Part of the sites	15
Tree growth	Every 5 years	All plots	858	Every 5 years	Part of the sites	15
Inventory of plants/ Ground vegetation	Every 1 - 5 years	Part of the plots	634	Every 1- 5 years[2]	Part of the sites	25
Metal chemistry of mosses	-	-		Every 5 years	Part of the sites	22
Soil chemistry	Every 10 years	All plots	862	Every 5 years	All sites	36/38
Soil water chemistry	Weekly – monthly	Part of the plots	250	Weekly-monthly	Part of the sites	41/51
Ground water and lake water chemistry	-	-		2-6 Monthly	Part of the sites	18/20
Runoff water chemistry	-	-		Daily-Monthly	Part of the sites	27/32
Inventory of birds	-	-		Every 3 - 5 years	Part of the sites	6
Phenology	Yearly	Part of the plots	44	-	-	
Microbial decomposition	-	-		Yearly	Part of the sites	15
Hydrobiology of streams and lakes	-	-		6 Monthly	Part of the sites	6
Remote sensing	5 or 10 yearly	Part of the plots	385	-	-	

[1] At some plots only litterfall excluding the chemical composition of falling leaves and needles
[2] Includes a separate survey on trunk epiphytes and aerial green algae.

An overview of the relevant key parameters which are available in the various surveys and studies in both programmes is given in Table 2. The number of parameters assessed within the surveys is larger, but this table is restricted to a number of selected key parameters, that give an adequate description of (i) the ecological and chemical condition of the ecosystem and (ii) the stresses on that ecosystem (De Vries, 2000). The relevance of the various parameters follows directly from the objectives of both ICP Forests Level II and ICP Integrated Monitoring. Some of the parameters are mandatory, others are optional. The responsibility for selecting the sample plots and for choosing optional parameters lies with the National Focal Centres (NFCs). As a result, the intensity of the monitoring activities and the sets of parameters assessed are subject to national peculiarities.

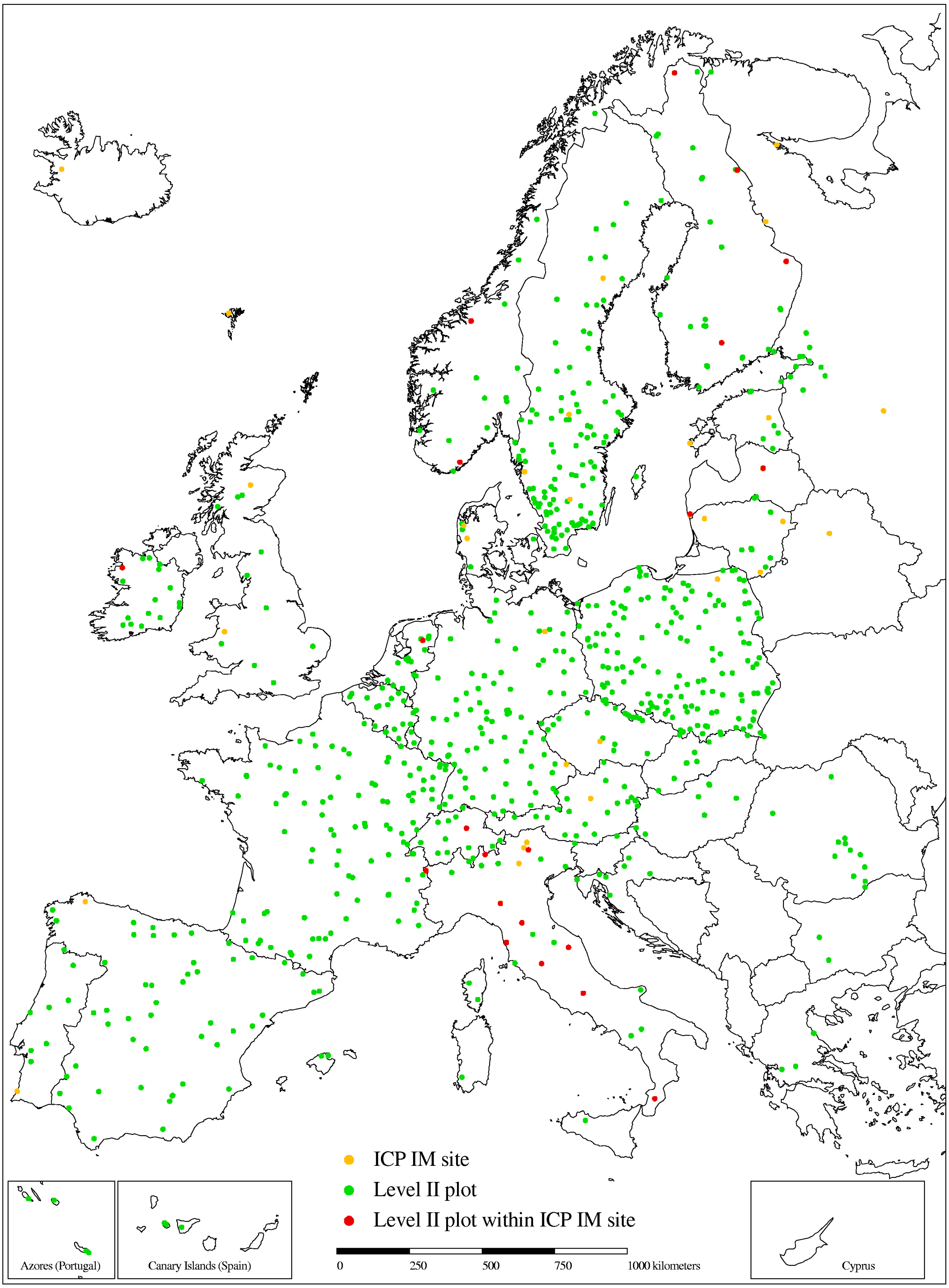


Figure 1: Locations of the sites of ICP IM and the Level II plots of ICP Forests

Table 2: Key parameters describing the 'ecological and chemical' conditions of forests and aquatic systems and the environmental stress on those systems assessed at ICP Forests and ICP IM plots

Type of parameter		Key parameters ICP Forests Level II	Key parameters ICP Integrated Monitoring
Site factors	Stand characteristics Site characteristics	Tree species, tree age, climatic region, altitude, soil type	- plot scale information on vegetation type, dominant tree species and soil type. - Catchment/Site scale information on altitude, vegetation type, soil type
Stress factors	Biotic stress	Easily assessable damage types	Easily assessable damage types on trees
	Air pollution	SO_4, NO_3, NH_4, Ca, Mg, K, pH in bulk deposition and throughfall (sometimes stemflow)	SO_4, NO_3, NH_4, Ca, Mg, K, pH in bulk deposition and throughfall, (sometimes stemflow).
	Ambient air quality	Passive sampling of O_3, SO_2, NO_2, NO_3+HNO_3, NH_3+NH_4	Measurement of gases and aerosols: O_3, SO_2, NO_2, NO_3+HNO_3, NH_3+NH_4
	Meteorology	Precipitation, temperature, wind speed and direction, global radiation, air humidity	Precipitation, temperature, wind speed and direction, global radiation, air humidity
Biological condition	Crown condition	Defoliation, discoloration	Defoliation, discoloration
	Increment	Diameter at breast height, tree height	
	Ground vegetation	Species composition and coverage	Species composition, coverage of species on permanent vegetation plots
	Soil biology		Weight loss due to decomposition, phosphatase activity of soil[1)], soil respiration[1)], N-mineralization[1)]
	Ozone injury	Damage of foliage due to excessive ozone exposure	
Chemical condition	Foliar composition		
	- major nutrients	N, P, S, Ca, Mg, K, N/P, N/Mg, N/K	N, P, S, Ca, Mg, K, C
	- minor nutrients	Fe, Mn, Cu, Zn	Fe, Mn, Cu, Zn
	- toxic elements	Al, Pb, Cd	Al, Pb, Cd
	Soil composition		
	- carbon	C	C
	- nutrients	N, P, Ca, Mg, K, C/N, N/P	N, P, exchangeable Ca, Mg, K
	- acidity	pH, base saturation[2)]	pH, base saturation
	- toxic elements	Pb, Cd, Cu, Zn	Pb, Cd, Cu, Zn
	Soil solution chemistry	SO_4, NO_3, NH_4, Ca, Mg, K, Al, Fe, Mn, pH, DOC	SO_4, NO_3, NH_4, Ca, Mg, K, Al, Fe, Mn, pH, DOC
	Surface water chemistry		SO_4, NO_3, NH_4, Ca, Mg, K, Al, Fe, Mn, pH, DOC

1) This parameter can be calculated from the mandatory meteorological parameters
2) These parameters are yet hardly or not available

2.2 Differences between ICP Forests Level II and ICP Integrated Monitoring

As detailed above, both programmes are aiming at quantifying key biogeochemical fluxes and understanding complex cause-effect relationships in ecosystems. There are, however, two main differences in the approach: i) the ICP IM sites are mostly catchments (including intensively studied plots); ii) most ICP IM sites are located in undisturbed areas (e.g. natural parks or protected areas), whereas the Level II plots have been chosen among characteristic forest ecosystems. The ICP IM is also more loosely co-ordinated, with variable implementation of the monitoring scheme and amounts of data available from the different sites. Assessment of air pollution effects on forest conditions (crown and foliar condition, growth) has been given very limited attention within ICP IM because this has been seen as the task of ICP Forests. Due to the fact that some of the ICP IM related activities started already in the mid-1980s, assessment of trends in chemical variables (deposition, surface waters) has been one of the key activities within ICP IM (e.g. Forsius et al., 2001; Moldan et al., 2001).

The conceptual background for the ICP IM is the well-known integrated work carried out at catchments like Gårdsjön (Munthe et al., 1998) and Hubbard Brook (Likens et al., 1996). Due to the focus on catchment scale, much assessment work within ICP IM has dealt with effects on surface waters and catchment-scale budgets and dynamic model applications. If properly co-ordinated, ICP IM and Level II of ICP Forests thus can provide complementary information. In some countries (e.g. Finland, Ireland, Italy, Norway) the two programmes are partly integrated so that some Level II plots are located within the ICP IM catchments. The use of common sites and a close cooperation between the National Focal Centres of both ICPs is clearly the most cost-efficient way to carry out monitoring and research on ecosystem effects.

2.3 Gaps in the monitoring set-up

Both programmes are executed by national scientists, following internationally agreed methods. Nevertheless sometimes discrepancies occur with the agreed methods on national or regional scale.

In the ICP IM, there is a general need for catchment-scale information on many key parameters (e.g. biomass). The heterogeneous ICP IM database has caused problems in e.g. the use of multivariate gradient analysis for assessing effects on vegetation (de Zwart, 1998). In the ICP Forests similar problems were encountered.

Monitoring design and data assessment methods

Considering the sampling design, one has to bear in mind that both, ICP IM and ICP Forests Level II plots were selected at a preferential basis with no explicit indication of the target population of concern and with no explicit indication of the model linking the sample plots/sites to the target population. This is a limit for statistical inference, and extrapolation of results to sites other than those being monitored is problematic (Ferretti, 1998; Scott, 1998; Koehl et al., 1994).

Other aspects involve the measurement errors, which may affect both, investigations involving visual assessment (e.g. ground vegetation and crown condition) and those with technical equipment. Both are not yet completely harmonised at European scale (e.g. Innes et al., 1993; Ferretti, 1999; Ghosh et al., 1995; Draaijers et al., 2000). In extreme cases, methodological differences between countries can account for more then 30% of the variance in crown condition, being more than the variance explained by the selected predictors.

A second aspect concerns the sampling design of the various measurements at the plot level. Also in this case the problems are similar to those discussed above as the sampling requirements of independency, casuality and known probability are not always met when locating the various measurement at the plots/sites (Ferretti and Nibbi, 2000).

Included parameters and variables

The adequacy and effectiveness of the ICP Forests Level II programme has been assessed by evaluating whether the current programme is sufficient to fulfil its aims (De Vries, 2000). Major limitations in data gathering were considered to be the lack or limited information on:

- Biotic stresses (pests/diseases). The programme focuses on the impacts of climate and chemicals (nutrients, acidity), but efforts towards more comprehensive information on biotic stress were launched recently.
- Gaseous exposure of certain pollutants: since these data are optional, ambient air quality is only assessed at a limited number of plots.

Both aspects have been picked up in the meantime.

Furthermore, there is only limited information available with respect to effects on roots, such as parameters describing fine root growth, mycorrhizae frequency, and on soil micro organisms/fauna. The programme is strongly focused on above ground effects (crown condition, growth and ground vegetation). The inclusion of data on soil fauna is, however, considered less relevant since this is a topic that is specifically related to soil pollution by heavy metals, which plays a less important role on a European scale. It seems more important to get adequate insight in the occurrence of pests and diseases. The fact that concentrations of SO_2, NO_x and NH_3 in air are only measured on 79 plots is a data lack. Additional data can be obtained from other monitoring programs, but do lack geographic focus in that case. The lack of ozone data is a limitation that receives further attention. At present, actions are going on to gain insight in ozone concentrations on most of the plots. A focus on ozone on the monitoring plots themselves seems relevant considering the phytotoxic impact of this air pollutant. Regarding the ICP IM, the data needs are largely the same as for the Level II programme and the same limitations apply in general.

3 Results of the Monitoring programmes

3.1 Approach

This sub-chapter summarises results of the two Monitoring Programmes in view of policy questions related to impacts of environmental stress factors, including climate change and air pollution (acidification, eutrophication and toxic elements), on the condition of both forest and aquatic ecosystems. In the following sub-chapters the most relevant results of the two monitoring programmes are described:

– Relationships between the crown condition of trees and environmental factors;
– Relationships between the species composition of the ground vegetation and environmental factors;
– Carbon sequestration in forest trees and forest soils;
– Impacts of atmospheric inputs of heavy metals on the metal concentrations in soil, soil solution, and foliage as well as surface waters;
– Impacts of atmospheric inputs of nitrogen and sulphur on the leaching of those compounds: element budgets;
– Assessment of trends in deposition and surface water quality;
– Impacts of future scenarios of atmospheric deposition on the ecosystem condition, specifically the soil water and surface water chemistry.

An overview of relevant stress parameters in the various relationships is given in Table 3.

Table 3: Overview of key stress factors for different effects included in the various studies, hypothesis for data evaluation.

Compartment	Effect	Key stress factors					
		nitrogen	acidity	ozone	metals	meteorology	biotic
Tree	Crown condition	+	+	(+)	-	+	+
Ground vegetation	Species diversity	+	+	(+)	+/-	+	(+/-)
Soil	Quality: metals	+	+	-	+	-	-
	Carbon storage	+	(+)	-	-	+/-	-
Soil water	Chemical composition (budgets)	+	+	-	-	+	-
Surface water	Chemical composition (future response)	+	+	-	-	+	-

[1)] A '+' signifies that an impact is expected, whereas a '-' implies the reverse. A '+/-' signifies that the impact is likely to be small. Values in brackets were not considered in the study considered.

3.2 Relationships between crown condition of trees and environmental factors

Approach to the study

The defoliation and discoloration are assessed extensively on the European scale (Level I), on the Level II plots and on the sites of the ICP Integrated Monitoring. On the European scale they were used to identify spatial patterns and the temporal development of the crown condition. The parameters can be seen as an integrative indicator for stress, reflecting adaptation mechanisms to shortages, e.g. in nutrient or water supply. However, they are of low specifity, which restricts the interpretation of possible cause-effect relationships.

Today, from the plots of the large scale monitoring valuable time series of crown condition assessments exist as well as data from the soil condition survey and the analysis of element contents of leaves and needles. In first integrative studies on the effects of environmental factors (climate, chemicals), carried out with multivariate statistics, effects of ozone, sulphur and nitrogen deposition on crown condition, as well as climate, could be detected (Klap et al., 2000; Seidling, 2001). The investigation of effects as time trends, stratified according to tree species and geographic region, yields more plausible results, confirming the results from other regional studies with data comparable to the extensive Level I monitoring.

At present correlative studies within the ICP Forests Level II Programme have been carried out for the relation of crown condition, foliar chemistry, soil chemistry, soil solution chemistry and species composition of the ground vegetation with environmental factors, focusing on crown condition versus atmospheric deposition (De Vries et al., 1998, 1999, 2000a, 2002). Those statistical relationships have been derived, using knowledge on the various influencing factors. The various studies were carried out with different statistical approaches including ordination techniques and multiple regression models.

Correlative crown condition study at ICP Forests Level II plots

Here, an example of a correlative crown condition study carried out approximately 262 plots where throughfall data were available is reported. The study was conducted to analyse the impact of different environmental factors on the defoliation of pine, spruce, oak and beech. Results showed that 30-50% of the variation in defoliation could be explained by the variation in stand age, soil type, precipitation, N and S deposition and foliar chemistry (Table 4). Highly significant adverse relations were found between defoliation and stand age for all tree species except pine. The defoliation of spruce and oak appeared to be larger in poorly buffered sandy soils compared to well-buffered clayey soils.

Table 4: Overview of the predictor variables explaining defoliation of the 4 most represented tree species of the Level II Plots with the number of plots (n) and the percentage accounted for ($R^2_{adj.}$).

Variable	Scots pine	Norway spruce	pedunculate oak	common beech
Soil type		*		
Age (yr)	+	++	+	++
Precipitation ($mm.yr^{-1}$)	+	--		
Temperature (^0C)			-	--
N deposition ($mol_c.ha^{-1}.yr^{-1}$)		-	++	+
S deposition ($mol_c.ha^{-1}.yr^{-1}$)		++		
Foliar N content ($g.kg^{-1}$)	+			
Foliar Ca content ($g.kg^{-1}$)		--	++	
N	59	95	33	35
$R^2_{adj.}$	21	35	44	48

* for soil type implies that this variable was significantly related to defoliation
++ highly significant and positive correlated with response variable
+ significant and positive correlated with response variable
-- highly significant and negative correlated with response variable
- significant and negative correlated with response variable

Impacts of foliar contents on defoliation were generally small. An increase in precipitation and in N deposition sometimes caused an increased defoliation and sometimes the reverse was true. This conclusion is in line with results from other correlative studies on the impact of acid deposition (Müller-Edzards et al., 1997; Klap et al., 2000; Hendriks et al., 2000). There are possible explanations for this, such as:

– A negative effect of precipitation due to excessive wetness and a positive effect by a decrease in drought stress;
– A negative effect of N deposition in N saturated systems and a positive effect of an increased N availability in nutrient poor forests.

The results are considered as a first step for the Level II evaluation. An in-depth interpretation was still hampered by a lack of information on stand history, pests and diseases and air quality on most of the plots and by the relatively small data set used. The same holds for studies at Level I plots. When more data become available, the relationship may be improved by including (see e.g. Klap et al., 2000):

- The temporal correlations between the repeated observations on the same site (geographical data) and the spatial correlation between neighbouring sites;
- Prolonged or delayed effect of certain stress factors on the forest condition (so called prolonged or delayed effects). This holds specifically for climatic stress factors (such as an extreme drought or frost period), but it may also hold for a severe acute event of atmospheric pollution;
- The occurrence of interactions between predictor variables in the regression model. For instance, it might be necessary to include interaction terms between meteorological stress variables and soil variables and bio-geographic region;
- The use of threshold values with respect to the stress factors, such as critical concentration levels for ozone in the atmosphere or critical values for the nutrient contents in foliage. When values of stress factors are known (based on process oriented research on causal dose-effect relationships) their influence can be neglected below an assumed critical limit. One may, however, also try to derive a critical level from available data.

Evaluations of the soil chemistry, tree condition, and nutritional state of the trees on Level I plots in Germany indicate that, if high percentages of nutrients, esp. magnesium, are bound in the organic layer, compared to the mineral soil, the forest condition is poor. This is probably due to the restriction of the rooting zone to the upper soil; under those conditions trees are more often subjected to drought and nutrient stress in dry periods, when water supply is short and mineralization of elements from organic matter is hindered. However, conclusions are not simple to draw, and a multitude of interactions may occur, depending on the site quality, tree species, and stand and deposition history.

Correlative crown condition study at ICP IM plots

As indicated above, the assessment of relationships between the crown condition of trees and environmental factors has been given very limited attention within ICP IM. De Zwart (1998) carried out an exploratory multivariate statistical gradient analysis of possible causes underlying the aspect of forest damage at ICP IM sites. These results suggested that for conifer defoliation, discolouration and lifespan of needles are for respectively 18%, 42% and 55% explained by the combined action of ozone and acidifying sulphur and nitrogen compounds in air.

From this and previous ordination exercises it was concluded that the applied statistical techniques are capable of revealing the underlying structure and possible cause-effect relationships in complex ecological data, provided that analysed gradients have an adequate range to be interpolated. Since the data obtained was unexpectedly poor in the span of environmental gradients, the results of the presented statistical ordination only indicated correlative cause-effect relationships with a limited validity. The poor span of gradients could be attributed to the relative scarcity of biological effect data and the occurrence of missing observations both in the chemical and biological data sets. It was concluded that the power of impact assessment would increase considerably with improvements in the vegetation monitoring and related data reporting within ICP IM and inclusion of additional sites, such as those of ICP Forests.

3.3 Relationships between the species composition of the ground vegetation and environmental factors.

Variation in species composition

The species composition of the ground vegetation, assessed on both Level II (ICP Forests) and Integrated Monitoring (ICP-IM) plots, is an indication of the floristic biodiversity of forest ecosystems. These data offer a unique opportunity to relate the species composition of the ground vegetation to environmental factors, including atmospheric deposition. This was recently done with Level II data to identify the environmental factors that most strongly determine the species diversity of the ground vegetation. If such factors are known, it may be possible to more precisely assess threats to species diversity, to which local governments might anticipate.

First an evaluation of ground vegetation data in terms of species diversity, indicated by the Simpson index, was carried out with available data from 674 plots (Figure 2). The value of this index is higher when more species occur. The map only includes higher plants, since not all countries included mosses and lichens in their ground vegetation assessments. The results show that there are large differences in species diversity of the plots throughout Europe.

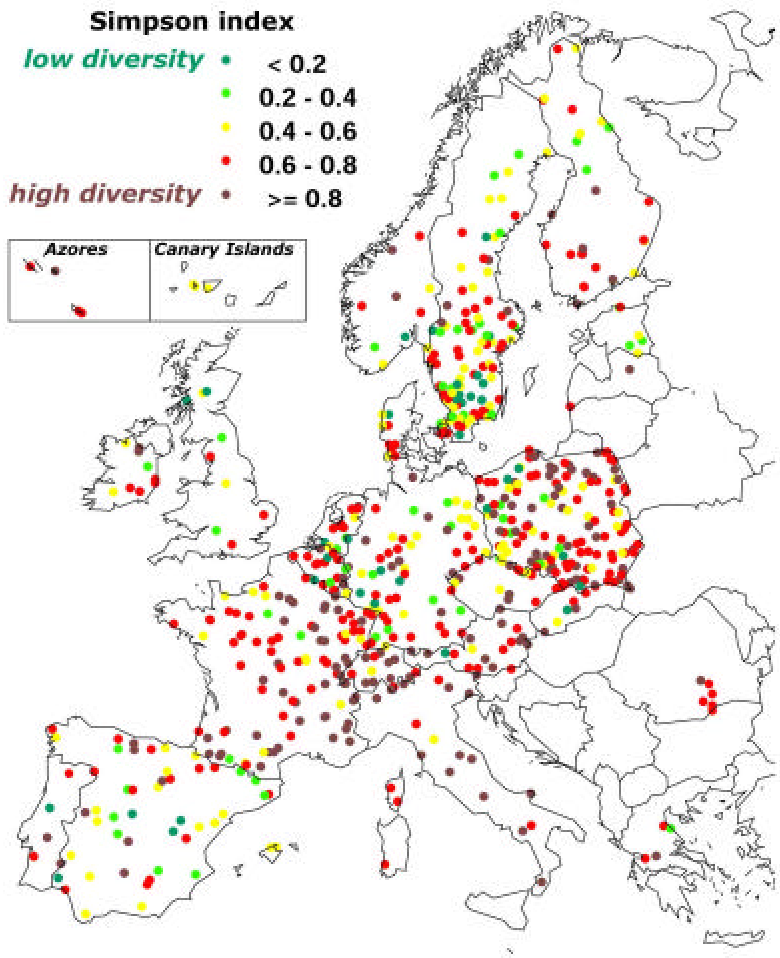


Figure 2: Species diversity, as expressed by the Simpson index, at 674 unfenced Level II plots, mosses and lichens excluded, assessed in 1998-1999.

Species diversity of the ground vegetation and environmental factors

Relationships between species diversity of the ground vegetation and environmental factors were evaluated on approximately 200-360 plots for which combined data sets were available. Included environmental factors were: (i) soil data, such as soil type and element contents in the humus layer and the mineral topsoil, (ii) climatic data, such as climate zone, temperature, precipitation and altitude, (iii) tree species and (iv) atmospheric deposition data of NH_4, NO_3, SO_4, Ca, Mg, K, Na and Cl. In the latter case, use was made of bulk deposition data that were available for 360 plots and throughfall and total deposition data that were available for 194 plots. In the latter analyses, bulk deposition was also used for the sake of comparison. Results of the analysis (Table 5), show that approximately 15%-20% of the variation in the abundances of the various species occurring in the ground vegetation could be explained by the various environmental factors. The explained variance is almost exclusively due to the actual soil situation (especially the pH of the organic layer and the mineral topsoil), tree species and climatic variables in terms of climatic zone, altitude, precipitation and temperature (Table 5). Only a very small portion of the explained variance is due to atmospheric deposition. The impact of anthropogenic N deposition could not or hardly be found in the models using bulk and total deposition but in the model using throughfall, it explained approximately 1% of the variation. The effect of acid deposition may, however, have partly been hidden because of the relationship between acid deposition and actual soil pH. As stated above, soil pH was an important variable explaining ground vegetation composition and consequently it is likely that changes in soil pH, induced by air pollution, do affect the species composition. The explanation increases with 13% when country is included as an explicit predictor, but this mainly illustrates that part of the variation can be explained by differences in data assessment methods. It should be stressed that the weak effect of the 'deposition' predictors is only based on the spatial pattern of both vegetation and predictors. It may still be possible that there is a strong effect of deposition on vegetation in time, but such a study will only become possible when sufficient repetitive measurements are available.

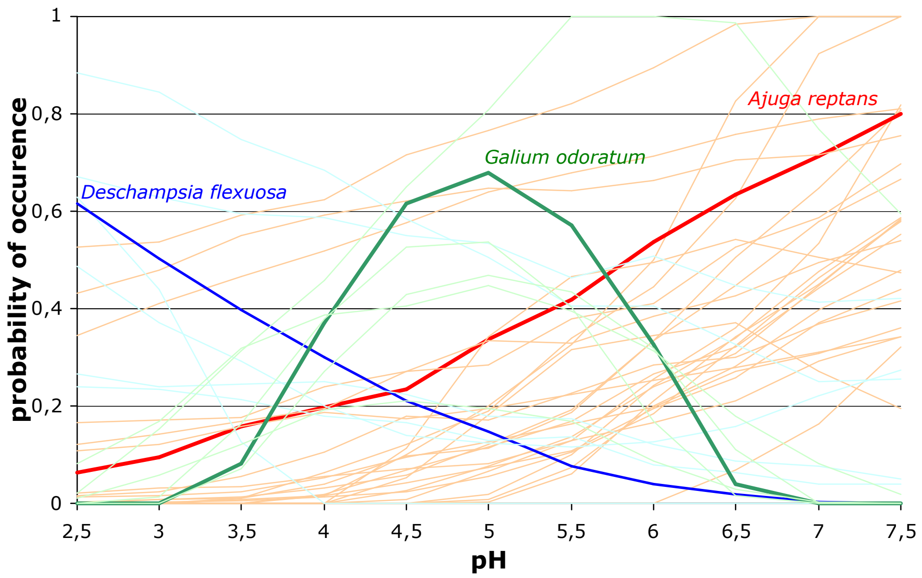
Tabel 5: Percentage explained variance of the species abundances in the 'significant' model using various selections of plots and deposition variables

variable group	360 plots, bulk deposition	194 plots, bulk or total deposition	194 plots, throughfall
Actual soil situation	5.8%	7.8%	7.6%
Climate 1)	4.9%	6.1%	5.6%
Tree species	3.1%	4.9%	4.1%
Deposition: non-anthropogenic (K, Na)	0.3%	0.0%	2.1%
Deposition: anthropogenic (NH_4, NO_3)	0.4%	0.0%	1.2%
SUM	**14.5%**	**18.7%**	**20.7%**

1) Includes climate zone, altitude, temperature and precipitation

Occurrence probability of individual species and environmental factors

Relationships between the occurrence probability of individual species and environmental factors species were also investigated for more than 300 different individual species. This resulted in response curves expressing the probability of occurrence for different species under changing environmental factors. An example of such a response curves for 36 selected species against soil pH is given in Figure 3. Results show that most species have their optimum at more basic conditions whereas at acidified sites fewer and specifically adapted species will become more abundant. Based on the presented results dynamic models are foreseen to be developed in the coming years. They will allow simulations that predict changes in ground vegetation composition under changing environmental conditions.



Species that prevail in acid soils (low pH) are: ***Deschampsia flexuosa,*** *Calluna vulgaris, Calamagrostis villosa, Vaccinium myrtillus, Vaccinium vitis-idaea, Picea abies, Sorbus aucuparia.*

Species that prevail in intermediate soils are: ***Galium odoratum****, Melica uniflora, Anemone nemorosa, Veronica officinalis, Hedera helix, Carex sylvatica.*

Species that prevail in alkaline soils (high pH) are: ***Ajuga reptans,*** *Viola alba, Melittis melissophyllum, Dactylis glomerata, Sorbus domestica, Cardamine bulbifera, Silene italica, Digitalis lutea, Festuca heterophylla Daphne laureola, Cruciata glabra, Ruscus aculeatus, Carex flacca, Stachys officinalis, Rubus caesius, Poa nemoralis, Carpinus betulus, Mercurialis perennis, Solidago virgaurea, Rosa arvensis, Luzula forsteri, Rubus idaeus, Prunus spinosa, Rubus ulmifolius, Arum maculatum.*

Figure 3: Probability occurrence curves for 36 species demonstrating a considerable influence of pH in the organic soil layer at 366 Level II plots.

The first assessment of vegetation monitoring data at ICP IM sites with regards to N and S deposition was carried out by Liu (1996). Vegetation monitoring was found useful in reflecting the effects of atmospheric deposition and soil water chemistry, especially regarding sulphur and nitrogen. The results suggested that plants respond to N deposition more directly than to S deposition with respect to vegetation indices.

3.4 Carbon sequestration in forest trees and forest soils

According to the Kyoto Protocol, countries can reduce emissions of CO_2 either by limiting fossil fuel consumption or by increasing net carbon sequestration in terrestrial sinks. However, the latter option is still limited to strictly defined cases of afforestation, land use change and additional management practices. The IGBP Terrestrial Carbon Working Group (Steffen et al., 1998), advocates, however, the use of a full carbon budget, including all potential terrestrial sinks over a sufficiently long time period, to be accounted for in international CO_2 emission reductions. This requires methods for reliable quantification of these C sinks.

The cycling of carbon cannot readily be separated from the abundance, state and cycle of other elements, esp. nitrogen, which in turn is tied to the cycling of other elements (Schulze et al, 2000). In the last years there has been a considerable progress in estimating stand biomass and growth trends, as a response to the detected discrepancies between tree growth as expected from yield tables, and the observed growth of trees (e.g. Spiecker et al., 1996).

Within the ICP Forests Level I Programme, an estimate of C sequestration in European forest soils was based on calculated nitrogen retention in the soils multiplied by the C/N ratio of the forest soil considered. N retention was calculated as a fraction of the N deposition corrected for N uptake, the fraction being dependent on the C/N ratio of the forest soil and the fraction NH_4 in deposition. In the calculation use was made of site specific estimates of N deposition and N uptake and measurements of C/N ratios for forest soils located in a systematic grid of 16 km x 16 km (Level I). The N deposition was based on modelled values at all (approximately 6000) Level 1 plots, being representative for approximately 2.0 million km^2 for Forests in Europe, excluding most of Russia. The actual N uptake was derived from stand age and available site quality characteristics, using forest yield tables to estimate the actual forest growth and deposition dependent N contents in the biomass. The actual C sequestration in stemwood (NEP) was calculated in a similar way using a C content of 50%. The N output was calculated as a function of the N deposition and the C/N ratio of the organic layer using presently available results on this relationship given in e.g. Matzner and Grosholz, 1997, Dise et al., 1998a, and Gundersen et al., 1998. An improvement of those estimates is foreseen, based on the input-output budget study at Level II plots presented in Section 3.6.

The estimated actual and long-term carbon sequestration in tree wood and forest soil for the whole of Europe, including Russia, is given in Table 6. Results for the actual carbon sequestration in tree wood appeared to be comparable to those based on CO_2 exchange fluxes (NEE) derived by Martin et al., 1998, based on the Euroflux sites. Long-term carbon sequestration data for tree wood are comparable to those derived from repeated forest inventories (Kauppi et al., 1992, and Nabuurs et al., 1998). Results for the forest soil were, however, much lower than those derived by Schulze et al., 2000, based on the C retention in eleven sites (0.21 Gton C yr^{-1}). The latter estimate is likely to be an overestimate, as it would imply that the C/N ratio of European forest soils is strongly increasing. There are no indications that this is the case. To the reverse, it is more likely that C/N ratios are decreasing, especially in areas with an elevated N deposition.

Table 6: Estimated net carbon sink for European forests due to net tree growth and net immobilisation in the soil

Region	Carbon sequestration in forest (Gton.yr^{-1})		
	Actual Tree wood	Long-term Tree wood	Forest soil
EU countries	0.184	0.073	0.0076
Other European countries	0.095	0.038	0.0016
Total	0.279	0.115	0.0093

The geographic variation in carbon sequestration is illustrated in Figure 4. The pattern in general follows the pattern of N deposition over Europe. It shows that C sequestration is small in Northern Europe, where the N input is low and nearly all incoming N is retained by the vegetation, and higher in Central and Eastern Europe where the N input is larger. The finding that C sequestration is negligible in northern Europe (boreal forests) is in line with results from Martin et al., 1998, based on flux measurements for CO_2. The major result of the calculation was that C sequestration by forest is mainly due to a net increase in forest growth, since the long-term sequestration in the soil is very limited. However, the net increase in forest growth will certainly stop sometime in the future; related specifications are not available until now. More information on the procedure and results is given in De Vries et al., 2000b.

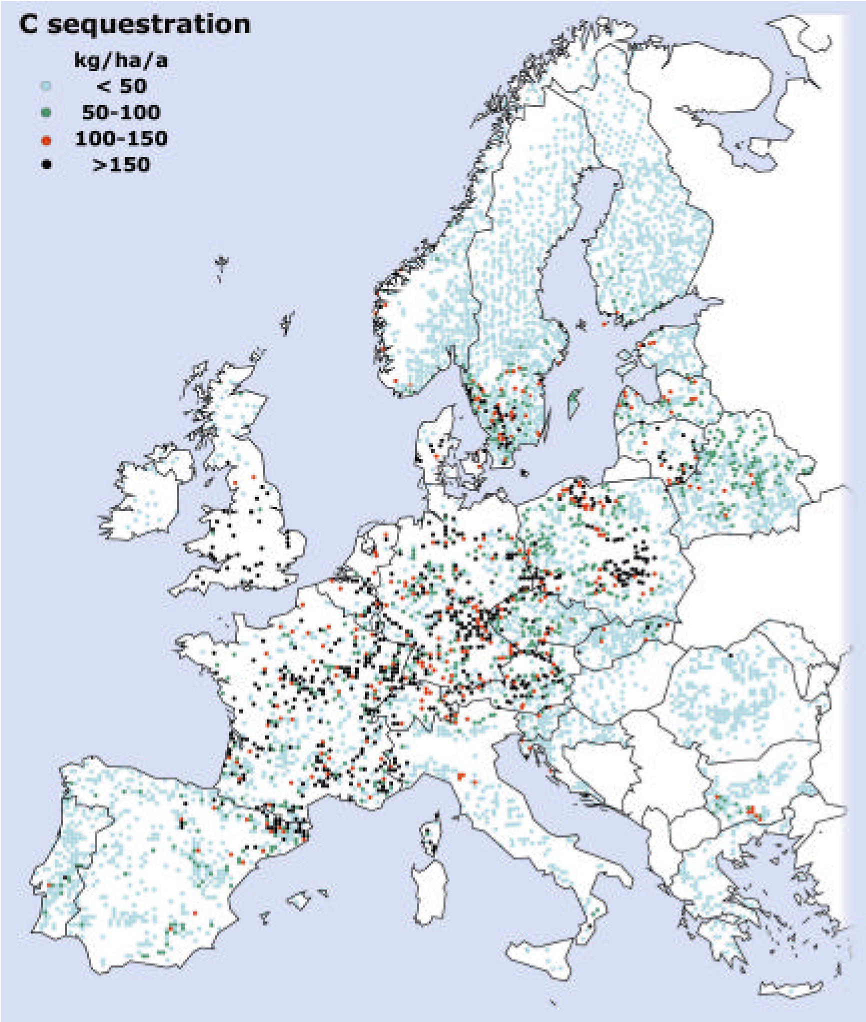


Figure 4: **Geographic variation of the calculated carbon sequestration over Europe, in ICP Forests Level I plots.**

3.5 Impacts of atmospheric inputs of heavy metals on the metal concentrations in soil, soil solution and surface water

Ecotoxicological risks associated with elevated heavy metal concentrations

The ecotoxicological risks associated with elevated heavy metal concentrations in terrestrial ecosystems include:

- Reduced microbial biomass and/or species diversity of soil micro-organisms and macrofungi, affecting microbial processes (see review by Bååth, 1989);
- Reduced abundance, diversity and biomass of soil fauna, especially invertebrates such as nematodes and earth worms (see review by Bengtsson and Tranvik, 1989);
- Reduced development and growth of roots and shoots (toxicity symptoms), decreased nutrient concentrations in foliar tissues (physiological symptoms) and decreased enzymatic activity (biochemical symptoms) of vascular plants including trees (see review by Balsberg-Påhlsson, 1989);
- Heavy metal accumulation followed by possible effects to essential organs on terrestrial fauna, such as birds, mammals, or cattle in agricultural soils. Those effects are important for cadmium (Cd), copper (Cu), mercury (Hg) and to a lesser extend lead (Pb), which can accumulate in the food chain (Jongbloed et al., 1994).

Concern about the atmospheric input of heavy metals (specifically Cd and Pb) to forest ecosystems is mainly related to the impact on soil organisms and the occurrence of bio-accumulation in the organic layer (Bringmark et al., 1998). With respect to Cu and Zn, the possible occurrence of deficiencies in view of forest growth is another relevant aspect, since they are essential metals. Another concern is related to the leaching of metals (specifically Cd and Hg) to surface water, having an adverse impact on aquatic organisms and causing bio-accumulation in fish, thus violating food quality criteria. In forests, most adverse impacts are to be expected from Pb and Cd, whereas Hg is of primary concern in aquatic systems, which are the priority metals for emission reduction.

Metal inventories on ICP Forests Level II plots

Up to now, studies within the context of the ICP Forests Level II Programme have been limited to a comparison of measured metal concentrations in forest soils to critical limits, while focusing on the organic layer. Criteria used for the judgement of heavy metal concentrations in the organic layer are given in Table 7. The upper values are based on a summary overview on critical metal contents in organic layers by Tyler, 1992, related to the effects on soil microbiota and soil invertebrates. The lower values are derived from values reported by Andersson et al., 1991, for unpolluted sites in northernmost Sweden.

Table 7: Criteria used for the judgement of heavy metal concentrations in the organic layer (Tyler, 1992 and Andersson et al., 1991)

Class/criteria	Heavy metal concentration ($mg \cdot kg^{-1}$)			
	Pb	Cd	Cu	Zn
Low (background)	<15	<0.35	<5	<35
Elevated	15-150	0.35-3.5	5-20	35-300
High (above a toxicity level)	>150	>3.5	>20	>300

The measured contents of heavy metals in the organic layer varied mostly (in 90% of all cases) between 17-230 $mg \cdot kg^{-1}$ for Pb, 0.1-2.3 $mg \cdot kg^{-1}$ for Cd, 5-39 $mg \cdot kg^{-1}$ for Cu and 15-284 $mg \cdot kg^{-1}$ for Zn. A classification of the results in terms of background values and critical values (Table 8), shows that Pb and Cu contents were elevated, compared to background level, on more than 90% of the plots. For Cd and Zn, this number was less and equalled 59% and 83% respectively.

The area exceeding a critical value related to effects on soil organisms was negligible for Cd but quite substantial for Cu (24%). There were also a few plots with Pb and Zn contents exceeding the critical value (Table 8). For Level I plots similar evaluations were carried out, resulting in comparable results. Only for copper the critical limit used was distinctly higher (60 $mg \cdot kg^{-1}$) resulting in only 3% of the plots exceeding the limit (Rademacher, 2001).

Table 8: Distribution (% of observations) over the classes 'low', 'elevated and 'high' of the heavy metal contents in the organic layer of stands within the ICP Forests Level II Programme

Class /criteria[1)]	Distribution (% of observations)			
	Pb (N=91)	Cd (N=69)	Cu (N=89)	Zn (N=86)
Low (background)	4.4	37.7	3.4	17.4
Elevated	83.5	59.4	69.7	77.9
High (above a toxicity level)	8.8	0.0	23.6	4.7

Metal budget studies on ICP IM plots

On ICP IM sites detailed heavy metal work on the site-specific level has been carried out over many years. This work has concerned both pools and fluxes of different heavy metals (e.g. Aastrup et al., 1995; Ukonmaanaho et al., 2001, Figure 5), and includes detailed work on mercury processes (e.g. Munthe et al., 1998).

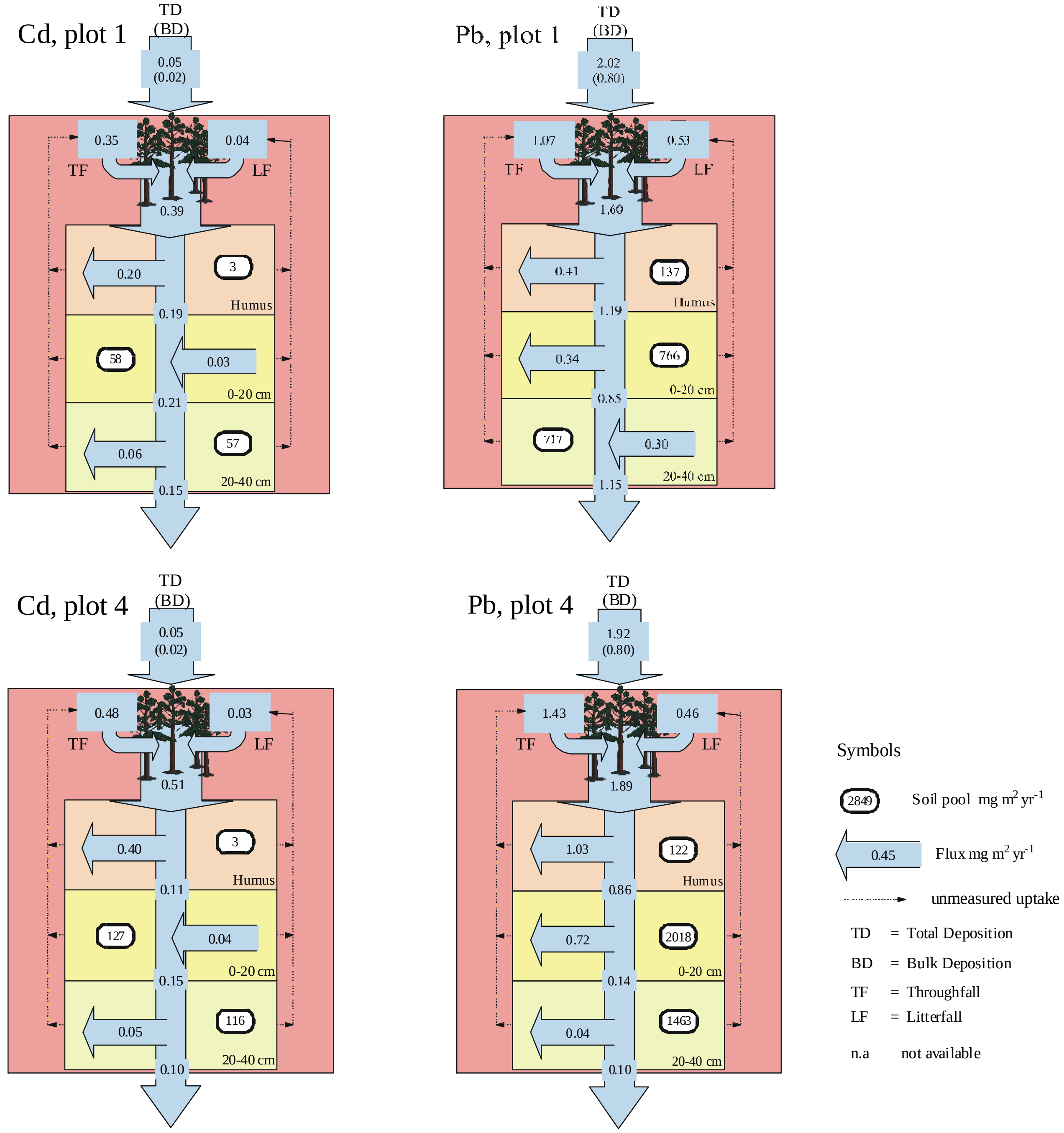


Figure 5: Stand-scale mean annual (1994-96) Pb and Cd fluxes and input-output budgets at the ICP IM site Hietajärvi (plots 1 and 4), eastern Finland (Ukonmaanaho et al., 2001).

Information on heavy metal concentrations was provided from 29 ICP IM sites with data on bulk deposition from 19 sites, moss chemistry from 22 sites, throughfall from 17 sites, stem flow, soil, groundwater and runoff from 10 sites, foliar and litter from 12 sites and on soils from 22 sites. So far results for Cd, Pb, Cu, Zn and to a small extent Hg have been considered.

In the years 1996-98 the ICP IM stations reported mean annual bulk deposition concentrations that were slightly lower than throughfall (Table 9). Additional metals have the origin from dry deposited pollution and from inner circulation. In the soil water, the range in concentrations are higher which implies both retention and loss. Ranges for runoff concentrations (site medians) showed much lower values, being the result of considerable retention in the soils (Table 9). The large variation in metal exports from forested catchments certainly reflect differences between sites as a consequence of actual metal deposition or other factors.

Table 9: Heavy metal concentrations (µg/l) in bulk deposition, throughfall, soil water and stream water of the catchment ecosystems in 10-19 sites over Europe.

Compartment	Cd	Cu	Pb	Zn	Ni
Bulk deposition	0.01-0.8	0.8-4.4	0.5-9.5	1-50	-
Throughfall	0.07-0.7	0.9-7	2-10	6-68	0.6-8
Soil water	0.07-1.3	0.24-5.4	0.26-27	11-138	6-12
Stream water	0.015-0.36	0.13-1.4	0.05-2	0.4-14	0.13-5

The input/output balance for Finnish and Swedish ICP IM catchments have been reported in scientific papers and national reports. There was considerable metal retention for Cd, Cu, Ni, Pb and Zn.; 80 to 95% of the total input. At some sites retention is somewhat lower for Cd and Zn, but even for these more mobile metals the general picture is an ongoing accumulation in the system.

Soils have large capacity of heavy metal storage due to adsorption to organic material. The present soil pools have resulted from a long deposition history. Reduced deposition and relocation between soil layers by leaching in recent years have not had full impact yet. The contents are higher in humus layers of ICP IM sites as compared to the mineral soil layers, with the exception of Ni (Table 10). Especially for Pb, a major component of long-range air pollution, there was a pronounced allocation to humus layers. The same is the case for Hg although the ICP IM data are scarce. More detailed evaluations of the ICP IM data are currently in progress.

Table 10: Heavy metal contents (µg/g) in the humus layer and in the mineral soil in the layer 30-40 cm of ICP IM sites.

	Cd	Cu	Ni	Pb	Zn
Humus layer	0.3-1	5-23	0.6-8	13-160	23-100
Mineral soil	0.01-1	0.7-21	2-24	4-46	3-85

3.6 Impacts of atmospheric inputs of nitrogen and sulphur on the leaching of those compounds: element budgets

Nutrient and proton budget studies on ICP Forests Level II plots

Input-output budget studies inform about possible accumulation or release of sulphur, nitrogen, base cations and aluminium in the ecosystem. More specifically, results about the input and output of those elements give insight in (i) the actual rate of acidification due to release of base cations and aluminium and (ii) the potential rate of acidification by immobilisation of S and N. Results about the input and output of Al and base cations (BC) give information about the mechanisms buffering the acid input. The ratio of Al to BC release is believed to be a key aspect with respect to soil mediated effects of acid inputs. These features can be used to derive critical deposition levels for forest soils (ecosystems), and the comparison of these loads with present loads will help assessing air pollution stress on the chemical ecosystem condition.

Input-output budget studies were carried out on approximately 120 Level II plots where reliable atmospheric deposition and soil solution chemistry data were available. Total deposition was calculated by adding measured throughfall and stemflow values below the forest canopy, while correcting for the effects of nitrogen uptake and base cation release by the forest canopy (leaves and needles), using data on bulk deposition in open field locations near the forest stands. Output fluxes were calculated by multiplying calculated water fluxes at a bi-weekly or monthly basis with measurements of element concentrations in soil solution. Details of the procedures are described in De Vries et al., 2001.

A comparison of median total deposition and median leaching fluxes (see Table 11) shows that median leaching fluxes are comparable to the deposition for sulphate, whereas leaching is generally much lower than deposition for nitrogen indicating that nitrogen is strongly retained in the soil. This indicates that SO_4 is still the dominant source of actual soil acidification, whereas acidifying effects of the higher nitrogen deposition are prohibited due to its retention. In oak stands, sulphate leaching is significantly higher than the input, whereas the reverse is true for pine stands. The high leaching flux of BC under oak stands is partly due to calcareous parent material from which weathering frees large amounts of base cations. The N leaching flux is lowest under pine trees, which is partly caused by the low water fluxes. The median leaching flux of base cations is generally higher than for aluminium, indicating that the average Al/BC ratio in the soil solution is mostly below 1.0, being considered as an average critical value above which impacts to roots may occur.

Table 11: Median total atmospheric deposition input (depo.), element leaching fluxes (leach.) and budgets of sulphate, nitrogen and total base cations(Ca+Mg+K) as well as aluminium leaching; (in $mol_c.ha^{-1}.yr^{-1}$).

Tree species	Number of sites	SO_4 depo.	Leach.	budget	N Depo.	leach.	budget	BC depo.	Leach.	budget	Al leach.
Pine	29	517	197	216	714	7	703	491	156	253	138
Spruce	51	685	590	16	1198	112	1040	469	331	94	774
Oak	15	637	1025	-256	962	212	686	519	2184	-911	30
Beech	20	634	604	-22	1340	135	984	489	717	30	326
Other	6	509	590	28	826	54	772	751	1149	-862	31
All	121	592	509	21	995	60	871	482	377	86	294

The geographic variation of the budgets for S and N is shown in Figure 6.

Sites with the highest S release are located in central Europe, where only recently a strong reduction in S deposition has taken place. Most probably the nowadays released S compounds have thus partly been deposited in earlier times. Sites with a net release of N are found in Belgium and north-western Germany. This corresponds to the area having received a high N deposition over a prolonged period of time. The astonishing high N retention in south-eastern Germany may be due to the fact that budgets are mainly based on the year 1996, which may lead to unrepresentative budgets due to the relatively low precipitation in this period.

An evaluation of 200 European “plot” and “catchment” budgets, aiming at the identification of indicators for the prediction of input/output relations, reveals that – on the European scale – the output of S can be predicted to a high degree with the variation of the input (Armbruster and Matzner, 2001). However, the attempt to validate the model with budget data from Level II sites in Saxony (Ore mountains, east Germany) failed (Figure 7). The measured S outputs exceed those predicted by far, indicating that the dissolution of sulphur pools in soils is an actually occurring process in these regions, leading probably to a delay of the recovery of ground and surface waters.

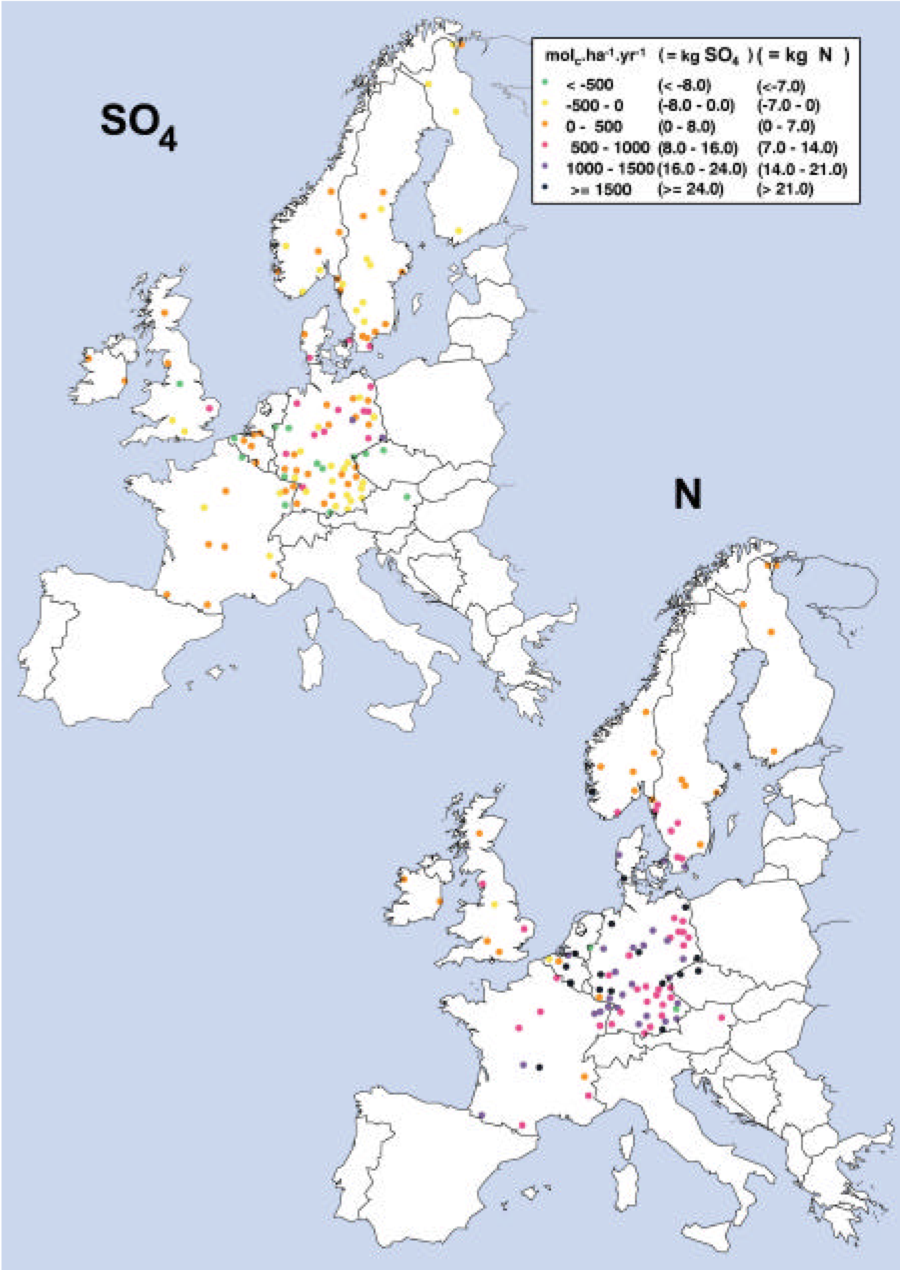


Figure 6: Geographic variation of the annual average budgets of sulphur and nitrogen in 1995-1998 at 121 Level II plots

This example underlines that the results of the Level II monitoring programme will add considerable value for further evaluations on the European scale. This has the advantage that the whole spectrum of possible geological substrates and soils with various deposition histories can be included, which yields the potential to come to a more holistic view of the patterns and processes of element fluxes on the European scale.

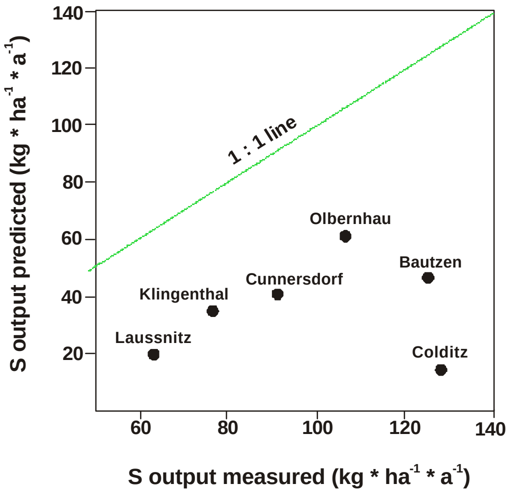


Figure 7: Measured versus predicted S output with the seepage water of Level II sites in Saxony, Germany (after Armbruster and Matzner, 2001). The prediction model applied was a regression of the form: S output = 1,0522 + 1,06782 * S input.

Nutrient and proton budget studies at ICP IM sites

The first ICP IM results of input-output and proton (hydrogen ion) budget calculations were presented in the 4th Annual Synoptic Report (ICP IM Programme Centre, 1995) and the updated results regarding the effects of N deposition were presented in Forsius et al. (1996). Data from selected ICP IM sites were also included in a European study for evaluating soil organic horizon C/N ratio as an indicator of nitrate leaching (Dise et al., 1998b). Starr (1999) has presented methods for calculation of water balance components at ICP IM sites. New results regarding the calculation of fluxes and trends of S and N compounds are presented in Forsius et al. (2001).

Figure 8 shows the relationship between N deposition and N output flux, and C/N ratio of the forest floor and N output flux observed at the ICP IM sites. A critical deposition threshold of about 9-10 kg N·ha^{-1}·yr^{-1}, indicated by several previous assessments, was confirmed by the input-output calculations with the ICP IM data. The output flux of nitrogen was strongly correlated with key ecosystem variables like N deposition, N concentration in organic matter and current year needles, and N flux in litterfall. Soil organic horizon C/N-ratio seems to give a reasonable estimate of the annual export flux of N for European forested sites receiving throughfall deposition of N up to about 30 kg N·ha^{-1}·yr^{-1} (Dise et al., 1998b; Forsius et al., 2001). The budget calculations showed a large difference between the sites regarding the relative importance of the various processes involved in the transfer of acidity, reflecting both the gradients in deposition inputs and the differences in site characteristics. The proton budget calculations showed a clear relationship between the net acidifying effect of nitrogen processes and the amount of N deposition. When the deposition increases also N processes become increasingly important as net sources of acidity.

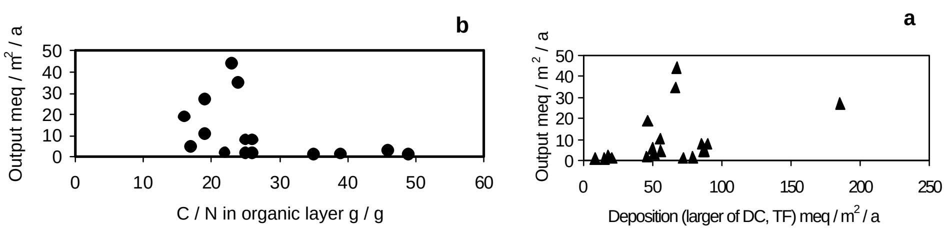


Figure 8: Relationship between N deposition and N output flux (a), and C/N ratio of the forest floor and N output flux (b) at the ICP IM sites (Forsius et al., 2001).

3.7 Trends in deposition and surface water chemistry

Empirical evidence on the development of environmental effects is of central importance for the assessment of success of international emission reduction policy (Working Group on Effects, 1999). CLRTAP was signed in 1979, when emissions of sulphur were quite high and acidification of waters, as well as damages to forests was of major concern. The sites of the ICP IM are mainly catchments where the stream and lake water chemistry of a defined region can be monitored. Consequently, many publications of the ICP IM deal also with changes of water quality, partly together with the results of the ICP Waters programme (Newell and Skjelkvåle, 1997; Stoddard et al., 1999). The results of these ICPs offer the chance to come to an integrated picture of the relevant processes and spatial patterns on the large scale. Due to the long time series available, environmental benefits of emission reductions can clearly be documented (Figure 9).

The first results of monthly ICP IM data on bulk and throughfall deposition as well as runoff water chemistry were presented in Vuorenmaa (1997). Corresponding to the reduced deposition of sulphur a recovery of freshwater quality is documented for many regions. An evaluation of the element budget data of 14 IM sites for the period 1988-1996 reveal, that despite the continuing clear trend to reduced S inputs the response pattern in the water chemistry of the individual sites is different (Vuorenmaa et al., 2000). Especially in central Europe, where S deposition load was highest for a long time (e.g. in the Czech Republic) the retained amounts of S in the soil seem to regulate the sulphur dynamics with still high outputs of S at reduced inputs. Data from southern Europe, mainly Italy, are relatively scarce (Mosello and Marchetto, 1995). They are from sites in the southern Alps and confirm the overall trends (Mosello et al., 1999). Extensions to other sites in Italy are planned (Ferretti, 2000). New calculations on the trends of N and S compounds, base cations and hydrogen ions have been made for ICP IM sites with available data across Europe (Forsius et al., 2001). The site-specific trends were calculated for deposition and runoff water fluxes using monthly data and non-parametric methods. Statistically significant downward trends of SO_4 and H^+ deposition were observed at a majority of the ICP IM sites.

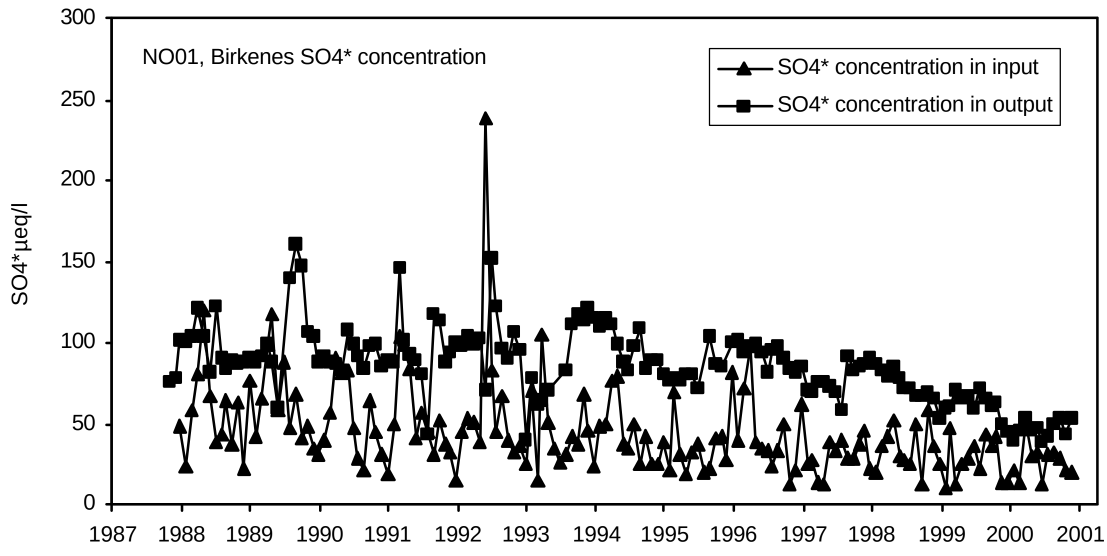


Figure 9: Changes in sulphate concentrations in deposition and streamwater in 1988-2000 at the ICP IM site Birkenes, southern Norway.

Decreasing NH_4 trends were more common than those of NO_3. Sites with higher N deposition and lower C/N-ratios clearly showed higher N output fluxes, and the results were consistent with previous observations from European forested ecosystems (Gundersen et al., 1998). Decreasing SO_4, NO_3, base cation and H^+ trends in output fluxes were observed at several sites in the Nordic countries and the Baltic States. The results partly confirm the effective implementation of emission reduction policy in Europe. However, clear responses were not observed at all ICP IM sites, showing that recovery at many sensitive sites can be slow and that the response at individual sites may vary greatly.

ICP IM data on water chemistry have also been used for a trend analysis carried out by the ICP Waters and presented in the 9-years report of that programme (Lükewille et al., 1997), and in a recent article of Stoddard et al. (1999). These results showed that regional recovery in surface water buffering capacity was observed in all studied European regions, but in only one region (of five) in North America. The lack of recovery was attributed to strong declines in base cation concentrations exceeding the decreases in sulphate. However, S adsorbing soils in central Europe, receiving very high amounts of S inputs in the past were under-represented in the study (Alewell et al., 2000). These sites exhibit considerable lags of response to reduced S inputs or even enhanced sulphur output due to the dissolution of sulphur pools in the soil. This is on the large scale observed in eastern parts of Europe after 1990, where drastic reductions of S inputs in forests occur (Raben et al., 2000).

Continued national and international research and monitoring efforts are thus needed to obtain scientific evidence on the recovery process to support future emission reduction policies.

3.8 Impacts of future scenarios of atmospheric deposition on the ecosystem condition, specifically the soil and surface water chemistry

Dynamic modelling approach

In a policy-oriented framework, dynamic models are needed to explore the temporal aspect of ecosystem protection and recovery. These models are flexible and can be adjusted for the assessment of alternative scenarios of policy importance. The critical load concept, used for defining the environmental protection levels, does not reveal the time scales of recovery. At the 17th session of the UN/ECE Executive Body in December 1999 the importance of the monitoring and dynamic modelling of recovery was underlined. A joint expert group on dynamic modelling has therefore been established under the CLRTAP, with the task of co-ordinating and assessing the modelling activities of the different ICPs, international research projects and national activities. This group has so far met two times in 2000 and 2001, and a strategy plan has been agreed upon. The results have been reported to the Working Group on Effects. Active modelling work is currently in progress at different spatial scales. The data gained within the framework of ICP Forests and ICP IM provide valuable data sets for the modelling of the possible effects of emission reduction on forest ecosystems.

Modelling studies at ICP IM sites

Dynamic models have been developed and used for the emission/deposition scenario assessment at selected ICP IM sites (e.g. Forsius et al., 1997, 1998a, 1998b; Posch et al., 1997; Jenkins, 2001). A study carried out with 5 data sets from ICP IM sites (Forellenbach, Gårdsjön, Birkenes, Afon Hafren, Hietajärvi), and calibrated with measured data from 1990-1994, indicates recovery of soils and waters from acid load, as expected (Forsius et al., 1998a). However, the authors pointed out that there were uncertainties regarding the implementation of the nitrogen dynamic and effects of possible N saturations (MAGIC, SAFE, SMART), due to the gaps in knowledge on this topic at present. Further uncertainties arise from the unknown relations between possible climatic changes, in combination with a surplus of nitrogen on acidified soils.

The modelling studies at ICP IM sites have shown, that the recovery of soil and water quality of the ecosystems is determined by both the amount and the time of implementation of emission reductions (e.g. Figure 10).

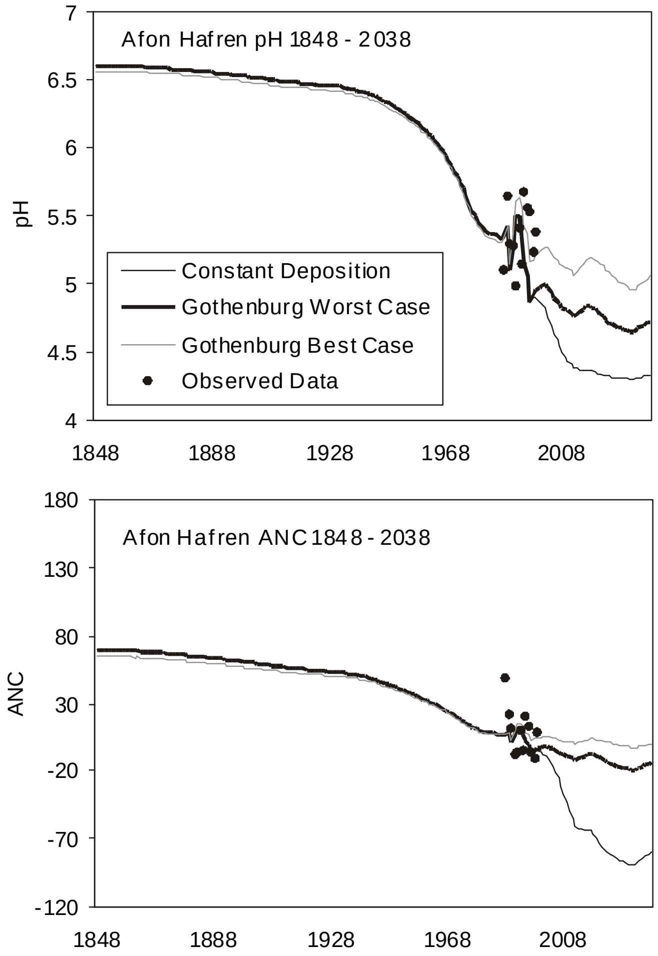


Figure 10: Simulated streamwater pH and ANC (µeq/l) calculated with the MAGIC model at ICP IM site Afon Hafren (GB02) with constant deposition and reductions agreed under Gothenburg Protocol (Jenkins, 2001).

According to the models, the timing of emission reductions determines the state of recovery over a short time scale (up to 30 years). The quicker the target level of reductions is achieved, the more rapidly the surface water and soil status recover. For the long-term response (> 30 years), the magnitude of emission reductions is more important than the timing of the reduction. The model simulations also indicate that N emission controls are very important to enable the maximum recovery in response to S emission reductions. Increased nitrogen leaching has the potential to not only offset the recovery predicted in response to S emission reductions but further to promote substantial deterioration in pH status of freshwaters and other N pollution problems in some areas of Europe.

The reduction in deposition of S and N compounds at the ICP IM sites, caused by the new "Protocol to Abate Acidification, Eutrophication and Ground-level Ozone" of the CLRTAP (a multipollutants-multieffects protocol), was estimated for the year 2010 using transfer matrices and official emissions. Implementation of the new protocol will further decrease the deposition of S and N at the ICP IM sites in western and northwestern parts of Europe, but in more eastern parts the decreases will be smaller (Forsius et al., 2001). This has implications for the future response patterns at these sites.

Plans for the future

Further development of the dynamic models is still needed. As far as abiotic processes are concerned, the modelling of acidification is mostly successful. The additional implementation of nonlinear biological processes with unknown interactions is in principal not solved today. However, for a risk assessment on the large scale simple empirical models may be sufficient for prediction of system behaviour, within certain limits (Armbruster and Matzner, 2001). Modelling the upper soil layers and the uptake of water and nutrients requires the knowledge of rooting depths. In this respect, there are considerable gaps in information on the quantities and distribution of the rooting zone. However, there are still uncertainties connected to the modelling of water flows, which can be studied in detail on intensive research plots like sites of the ICP IM programme (e.g. Hauhs et al., 1998).

At present, dynamic modelling at ICP Forests Level II plots is foreseen for 2003. Ultimately, modelling will not be limited to soil and soil solution chemistry alone, but will also include the prediction of changes in forest growth and species composition of the ground vegetation in response to scenarios for both changes in atmospheric deposition and climate. Such models will include empirical relationships, to account for the multiple effects of stressors on forest ecosystems. An example is the impact on ground vegetation, in which an evaluation of data from ICP Forest plots with multivariate statistical methods was used. In this way empirical response relations based on thousands of observations, allows the transfer of information found in in-depths studies to the large scale (regionalisation).

4 Summary and outlook

Aims

The ICP on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) and the ICP Integrated Monitoring of Air Pollution Effects on Ecosystems (ICP IM) are fairly closely related, both with also close connections to other programmes within the Working Group on Effects of UNECE. ICP IM monitors biological, chemical and physical state and processes with a catchment approach. ICP Forests contributes to increased understanding of forest ecosystems by a pan-European monitoring system for intensive and continuous monitoring of forest ecosystems (so called Level II-Programme) directed to air pollution, critical loads, pollution scenarios, carbon storage and indicators on forest ecosystem sustainability.

Approach

Level II is directed towards the most widespread forest ecosystems and the plots are located in managed areas, whereas the ICP IM sites mostly focus on natural, undisturbed forests. ICP Forests is using a plot or site approach while ICP IM mainly has the catchment approach. Included in both programmes are abiotic and biotic variables with the concept to find cause effect relationships between environmental driving forces, in particular atmospheric deposition and forest ecosystem reactions. Thereby, the aspects deposition, soil and vegetation are covered. Both ICP Forests and ICP IM determine hydrological balances and hydrochemical budgets for development and validation of models. ICP Forests focuses on soil models whereas ICP IM also includes output to surface waters showing the link to ICP Waters.

Spatial coverage

The Level II programme of ICP Forests has a considerable spatial coverage over Europe while ICP IM catchments are fewer and more unevenly distributed. Properly co-ordinated, the two programs are complementary in the concern of mainly natural and semi-natural forest sites. In ICP IM the interest is directed on unmanaged forests, i.e. natural old forest stands with long continuity often making up nature reserves. The sites comprise mature old forest stands with no ongoing wood volume increment as well as stands that have not reached maturity. In contrast to this, ICP Forests mainly deals with common and actively managed forests having a consecutive volume increment and being also subjected to harvesting and other forestry measures. Such activities create disturbance in the forest ecosystems as the canopy is opened and fixed nutrient elements and carbon is freed or removed in the harvesting process adding to the deposition impacts. Ideally, the combination of the two programmes would yield estimations of forestry impacts on the ecosystem, separated from long-range transboundary origin of elements in deposition.

Further benefits of programme co-operation could be the development and testing of models in ICP IM. Relevant models could then be adopted and applied on ICP Forests sites to assess large scale impacts from forestry measures.

For the two programs results on crown conditions, ground vegetation, carbon storage, heavy metals, element budgets of S and N, dynamic modelling of ecosystem conditions and trends in surface water chemistry are shown in this report. Evaluations of both programs are in general in line.

Crown condition

On European scale spatial patterns and temporal development of crown condition have been used as indicators for stress. Using multivariate statistics, effects of air pollutant and climate could be detected. Results revealed that 30% of variation in defoliation could be assigned to stand age, soil type, precipitation, 0_3 and S deposition and foliar chemistry. Gradient analysis suggest that ozone, acidifying sulphur and nitrogen explain 18%, 42% and 55%, respectively, of damage which is a major result of ICP Forests.

Effects of Environmental factors on ground vegetation

Relationships between species diversity of the ground vegetation and environmental factors that were evaluated at 366 Level II plots showed that 20% of the variation in the abundances of the various species occurring in the ground vegetation could be explained by soil, climate and tree species (indirectly influencing the light regime). A small portion of the explained variance is due to throughfall deposition chemistry, but this result is only based on the spatial pattern of both vegetation and predictors. There may be a strong effect of deposition on vegetation development in time, but such a study will only become possible when sufficient repetitive measurements are available. Results show, however, that soil acidification will negatively influence ground vegetation diversity in the forests. For various species, there is a significant relationship between the occurrence probability and soil pH. The pH in the organic layer also explains most of the variation in species numbers. In future a combination with ICP IM data is foreseen. An example is the validation of species composition, predicted by means of relationships with environmental factors derived at the Level II plots, on available data at the Integrated Monitoring plots.

Carbon sequestration

The increase in the carbon content in the atmosphere has gained increased attention in forestry and environmental policies of recent years. Until recently, estimations on sequestration in soils, especially the vertical distribution, are hardly available on the European scale and are in addition very uncertain. The data set of ICP Forsts is of particular interest as the increase in carbon content in the atmosphere can be mitigated by increased carbon sequestration in forest biomass and forest soils. First evaluations of Level II data were carried out for stand biomass and for soils. Estimations for the sequestration in both tree biomass and soil showed reasonable agreement with literature estimates based on CO_2 exchange flux measurements at a few intensively monitored sites, being upscaled to Europe. Using the data on C/N ratios and estimates on atmospheric N deposition at ICP-Forest plots, an estimate was given of the carbon sequestration in soils as compared to trees. The assumed relationship between carbon sequestration and nitrogen retention implies that low carbon sequestration is calculated in areas with low N deposition, such as the Northern countries and high carbon sequestration in high nitrogen deposition areas, such as in Central Europe. The results of the ICP Forests study show that the ultimate contribution of the soil in sequestering carbon is likely to be small. However, on a smaller time scale, there may be a larger role for the soil in sequestering carbon due to an imbalance in carbon entering the soil by litterfall and fine root turnover and leaving the soil by mineralisation.

Heavy metals

Elevated heavy metal concentrations in ecosystems means toxicological risks for terrestrial and aquatic biota. Special attention has been paid to Cd, Pb and Hg, where methyl-Hg is especially hazardous in aquatic systems. Heavy metal concentrations in the soil organic layer of ICP Forests plots exceeded background levels for Pb and Cu in 90% of the samples. For Cd (59%) and Zn (83%) the values were lower. An exceedance of the toxicity level was only considerable for Cu (near 25%) whereas it was only 5-9% for Zn and Pb, respectively. In-/output budgets for Finnish and Swedish ICP IM catchments showed retention of heavy metals, which means accumulation in the soil system.

Element budgets related to S and N deposition

Both programs studied ecosystem budgets for S, N, BC and Al revealing acidification and buffering capacities. It is also possible to use this information in dynamic models estimating future chemical conditions and in the calculation of critical loads that can be compared to actual loads. Results at more than 100 ICP Forests plots show that average sulphur deposition is close to average leaching. At several plots, the S outflow is still very high and even enhanced due to sulphur pool dissolution, indicating still important influences on acidification while nitrogen mainly is retained in the soil and therefore yet not contributing considerably to acidification processes. Mostly, the Al/BC ratio is below 1 and damage to roots is not likely to be substantial. Considerable variations occur, however throughout Europe.

Trend assessment

Within ICP Forests a comparison has been made between deposition in the nineties measured on Level II plots and in the eighties measured at nearby plots, showing downward trends of SO_4 and NO_3 deposition but not of NH_3. Within the ICP-IM program a trend analyses was carried out on deposition and soil water chemistry, showing downward trends of SO_4 and H^+ deposition with recovery in water quality in many regions. However, in some European areas earlier exposed to the highest S deposition, the S outflow is still very high and even enhanced due to sulphur pool dissolution. Recovery following deposition reduction has been found at a number of sites but uncertainties remain concerning influences from nitrogen and climate changes.

Dynamic modelling

Modelling has been used in both programs to estimate the recovery from acid deposition. Scenario assessment at the ICP IM sites showed the importance of further reduction, where the timing of the emission reductions is most important in the short time scale, while the magnitude is more important than timing in the long-term perspective. Results further showed that the gained improvements due to lower S loads could be mitigated by a still high N load, thus indicating the necessity of putting more emphasis on N emission reduction in the future.

Outlook

Obviously, ICP Forests has a larger spatial coverage of sites while ICP IM is more limited in this sense. Due to differing objectives, the same spatial distributions are not needed for ICP IM as for ICP Forests. Anyhow, also ICP IM covers important gradients, mainly across Europe. The plots include varying conditions and provides inputs for modified models. On the contrary, ICP Forests provides possibilities for calculations reflecting natural conditions on a wider scale. Further, ICP Forests includes managed forest while ICP IM mainly focusses on natural unmanaged forest and related land. These differences provide possibilities to evaluate effects of silviculture.

A limitation of both programmes is the choice of sites and catchments often being rather typical for forest stands on drained soils. The sites do not cover the total range of soil types on natural and seminatural landscapes. Often poorly drained and wet soils are avoided. These soils types, however, cover substantial areas and are crucial in catchments concerning water and nutrient turnover. Peatland and other wetlands cover extensive areas, especially in northern Europe, and have considerable influences on ecosystems on the landscape scale.

Indicator species adopted to key habitats on moist or wet soils in several cases give earlier signals on pollution impacts, compared to more common and trivial vegetation species. In addition, poorly drained and wet soils could have a great relevance for the monitoring of climate change effects.

Further gaps in the programmes concern the influence of gaseous components like ozone as well as full scale biotic stress considerations. ICP Forests however is working to close these gaps.

Further co-operation would be beneficial to both programmes. Most important in such co-operative monitoring would be the use of the same methods for relevant variables. Obviously, harmonisation partly already exists and it would be beneficial to continue this activity. Development of models for further application to a large scale of sites and co-ordinated with external network programmes would deliver new insights and understanding of how to maintain a sustainable environment and to follow recovery from air pollution. In addition there is a need for co-ordination in evaluation strategies between both programs.

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Annex 1: Addresses

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