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Convention on Long-range Transboundary Air Pollution

International Cooperative Programme on Integrated Monitoring of Air Pollution Effects on Ecosystems

James Kurén Weldon (ed.)

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Abstract

The Integrated Monitoring Programme (ICP IM) is part of the effect-oriented activities under the 1979 Convention on Long-range Transboundary Air Pollution, which covers the region of the United Nations Economic Commission for Europe (UNECE). The main aim of the ICP IM is to provide a framework to observe and understand the complex changes occurring in natural/semi natural ecosystems. This report summarizes the work carried out by the ICP IM Programme Centre and several collaborating institutes, including:

- A short summary of previous data assessments
- A status report of the ICP IM activities, content of the IM database, and geographical coverage of the monitoring network
- A report on long-term trends in precipitation, throughfall and runoff water chemistry at IM sites
- Analysis of changes in above ground carbon pools at the heavily disturbed IM site Aneboda (Sweden)
- National Reports on ICP IM activities

Keywords: Integrated Monitoring, ecosystems, small catchments, air pollution

Abbreviations

AMAP	Arctic Monitoring and Assessment Programme
ANC	Acid neutralising capacity
CCE	Coordination Centre for Effects
CDM	Centre for Dynamic Modelling (previously JEG DM), a body under ICP M&M
CL	Critical Load
CNTER	Carbon-nitrogen interactions in forest ecosystems
ECE	Economic Commission for Europe
eLTER RI	European Research Infrastructure that LTER Europe is building after being adopted by the 2018 ESFRI Roadmap. The RI is built by the two Horizon 2020 projects “eLTER PPP” (Preparatory Phase Project) and “eLTER PLUS” (Advanced Community project)
EMEP	Cooperative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe
EU	European Union
EU LIFE	EU’s financial instrument supporting environmental and nature conservation projects throughout the EU
Horizon 2020	H2020, EU Research and Innovation programme
ICP	International Cooperative Programme
ICP Forests	International Cooperative Programme on Assessment and Monitoring of Air Pollution Effects on Forests
ICP IM	International Cooperative Programme on Integrated Monitoring of Air Pollution Effects on Ecosystems
ICP Materials	International Cooperative Programme on Effects on Materials
ICP M&M	ICP Modelling and Mapping, International Cooperative Programme on Modelling and Mapping of Critical Loads and Levels and Air Pollution Effects, Risks and Trends
ICP Waters	International Cooperative Programme on Assessment and Monitoring Effects of Air Pollution on Rivers and Lakes
ICP Vegetation	International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops
ILTER	International Long Term Ecological Research Network
IM	Integrated Monitoring
JEG	JEG DM, Joint Expert Group on Dynamic Modelling. Now under the acronym CDM
LRTAP Convention	Convention on Long-Range Transboundary Air Pollution
LTER Europe	European Long-Term Ecosystem Research Network
LTER Network	Long Term Ecological Research Network
NFP	National Focal Point
SLU	Swedish University of Agricultural Sciences
TF	Task Force
Task Force on Health	Joint Task Force on the Health Aspects of Air Pollution
UNECE	United Nations Economic Commission for Europe
WGE	Working Group on Effects

Contents

Preface

Welcome to the 34th Annual Report, produced by the Programme Centre at the Swedish University of Agricultural Sciences. This year's Task Force meeting was held in Dessau-Rosslau, Germany. We thank our German colleagues for hosting a successful meeting! Minutes of the TF meeting may be downloaded from the IM website (text link below) and the ICP Waters website. Presentations from the meeting can also be found at the ICP Waters site. The cover photo for this year's report is of the IM site DE02 Neuglobsow.

Our British colleagues have kindly offered to host the 2026 Task Force Meeting in the Lake District (Cumbria, England), from 5-7 May. More information will of course be sent out nearer the time, but for now please save the date.

As well as the usual features, this edition of the annual report includes an update on concentrations of nitrogen (N) and sulphur (S) in the throughfall, precipitation chemistry and runoff water chemistry subprogrammes across the network from 2000 onwards, and a report on a project looking at the impacts on carbon pools of a huge increase in dead wood at a Swedish IM site.

Finally I would like to note that Salar Valinia's role as co-chair of IM has come to an end since the last edition of this report, and that we thank him for his efforts over the years.

James Kurén Weldon, on behalf of the Programme Centre

The Programme Centre team is as follows:

James Kurén Weldon – Head of Programme Centre
Karin Eklöf – Evaluation of heavy metals data
Martyn Futter – Senior researcher, with focus on modelling
Hampus Markensten – Validation of incoming data, updating the database, and handling data excerpts
Pernilla Rönnback – Database manager/administrator

The current chair of IM, Ulf Grandin, is also based in Sweden, facilitating close co-operation with the Programme Centre.

The website for IM can be found at www.slu.se/en/icp-im and a PDF version of the monitoring manual can be downloaded from this link, as well as minutes of meetings and previous editions of this report.

Comprehensive summary

Background and objectives of ICP IM

Integrated monitoring of ecosystems means physical, chemical, and biological measurements over time of different ecosystem compartments simultaneously at the same location. In practice, monitoring is divided into several compartmental subprogrammes which are linked by the use of the same parameters (cross-media flux approach) and/or same or close stations (cause-effect approach).

The International Cooperative Programme on Integrated Monitoring of Air Pollution Effects on Ecosystems (ICP IM, https://www.slu.se/en/icp-im) is part of the Effects Monitoring Strategy under the Convention on Long-range Transboundary Air Pollution (LRTAP Convention). The main objectives of the ICP IM are:

- To monitor 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.
- To develop and validate models for the simulation of ecosystem responses and use them (a) to estimate responses to actual or predicted changes in pollution stress, and (b) in concert with survey data to make regional assessments.
- To carry out 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 ecological effects of heavy metals, persistent organic substances, and tropospheric ozone to be determined. 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 nature reserves or comparable areas. The ICP IM network presently covers forty-eight sites from fifteen countries. The international Programme Centre is located at the Swedish University of Agricultural Sciences, in Uppsala, Sweden. The present status of the monitoring activities is described in detail in Chapter 1 of this report. A manual detailing the protocols for monitoring each of the necessary physical, chemical, and biological parameters is applied throughout the programme (Manual for Integrated Monitoring 1998, and updated versions, which can be downloaded from the website).

Assessment activities within the ICP IM

Assessment of data collected in the ICP IM framework is carried out at both national and international levels. Key tasks regarding international ICP IM data have been:

- Input-output and proton budgets
- Trend analysis of bulk and throughfall deposition and runoff water chemistry
- Assessment of responses using biological data
- Dynamic modelling and assessment of the effects of different emission / deposition scenarios, including confounding effects of climate change processes
- Assessment of concentrations, pools, and fluxes of heavy metals
- Calculation of critical loads for sulphur and nitrogen compounds, and assessment of critical load exceedance, as well as links between critical load exceedance and empirical impact indicators
- Evaluation and reporting of ICP IM data in relation to the revision process of the Gothenburg Protocol

Conclusions from international studies using ICP IM data

Input-output and proton budgets, C/N interactions

Ion mass budgets have proved to be useful for evaluating the importance of various biogeochemical processes that regulate the buffering properties in ecosystems. Long-term monitoring of mass balances and ion ratios in catchments/plots can also serve as an early warning system to identify the ecological effects of different anthropogenically derived pollutants, and to verify the effects of emission reductions.

The most recent results from ICP IM studies are available from the study of Vuorenmaa et al. (2017). Site-specific annual input-output budgets were calculated for sulphate (SO_4^{2-}) and total inorganic nitrogen (TIN = NO_3-N + NH_4-N) for 17 European ICP IM sites in 1990–2012. Temporal trends for input (deposition) and output (runoff water) fluxes and net retention/net release of SO_4^{2-} and TIN were also analysed. Large spatial variability in the input and output fluxes of SO_4^{2-} and TIN reflects important gradients of air pollution effects in Europe, with the highest deposition and runoff water fluxes in southern Fennoscandia, Central and Eastern Europe and the lowest fluxes at more remote sites in northern European regions. A significant decrease in the total (wet + dry) non-marine SO_4^{2-} deposition and bulk deposition of TIN was found at 90% and 65% of the sites, respectively. Output fluxes of non-marine SO_4^{2-} in runoff decreased significantly at 65% of the sites, indicating positive effects of international emission abatement actions in Europe during the last 25 years. Catchments retained SO_4^{2-} in the early and mid-1990s, but this shifted towards a net release in the late 1990s, which may be due to the mobilisation of legacy S pools accumulated during times of high atmospheric SO_4^{2-} deposition. Despite decreased deposition, TIN output fluxes and retention rates showed a mixed response with both decreasing (9 sites) and increasing (8 sites) trend slopes, but trends were rarely significant. In general, TIN was strongly retained in the catchments not affected by natural disturbances. The long-term annual variation in net releases for SO_4^{2-} was explained by variations in runoff and SO_4^{2-} concentrations in deposition, while a variation in TIN concentrations in runoff was mostly associated with a variation of the TIN retention rate in catchments. Net losses of SO_4^{2-} may lead to a slower recovery of surface waters than those predicted by the decrease in SO_4^{2-} deposition. Continued enrichment of N in catchment soils poses a threat to terrestrial biodiversity and may ultimately lead to higher TIN runoff through N saturation or climate change. Continued monitoring and further evaluations of mass balance budgets are thus needed.

Summary of earlier results from ICP IM studies

The first results of input-output and proton 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 European studies for evaluating soil organic horizon C/N-ratio as an indicator of nitrate leaching (Dise et al. 1998, MacDonald et al. 2002). Results regarding the calculation of fluxes and trends of S and N compounds were presented in a scientific paper prepared for the Acid Rain Conference, Japan, December 2000 (Forsius et al. 2001). A scientific paper regarding calculations of proton budgets was published in 2005 (Forsius et al. 2005).

The budget calculations showed that there was a large difference between the sites regarding the relative importance of the various processes involved in the transfer of acidity. These differences reflected 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.

A critical deposition threshold of about 8–10 kg N ha^{-1} yr^{-1}, indicated by several previous assessments, was confirmed by the input-output calculations with the ICP IM data (Forsius et al. 2001). 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 (Forsius et al. 1996). 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}. When stratifying data based on C/N ratios less than or equal to 25 and greater than 25, highly significant relationships were observed between N input and nitrate leached (Dise et al. 1998, MacDonald et al. 2002, Gundersen et al. 2006). Such statistical relationships from intensively studied sites can be efficiently used in conjugation with regional monitoring data (e.g., ICP Forests and ICP Waters data) in order to link process level data with regional-scale questions.

An assessment on changes in the retention and release of S and N compounds at the ICP IM sites was prepared for the 21st Annual Report (Vuorenmaa et al. 2012). Updated and revised data were included in the continuation of the work in the 22nd and 23rdAnnual Reports (Vuorenmaa et al. 2013, 2014). The relationship between N deposition and organic N loss and the role of organic nitrogen in the total nitrogen output fluxes were derived in Vuorenmaa et al. (2013).

Sulphur budgets calculations indicated a net release of S from many ICP IM sites, indicating that the soils are releasing previously accumulated S. Similar results have been obtained in other European plot and catchment studies.

The reduction in deposition of S and N compounds at the ICP IM sites, as a result of the implementation of the "Protocol to Abate Acidification, Eutrophication and Ground-level Ozone" of the LRTAP Convention ("Gothenburg Protocol"), was estimated for the year 2010 using transfer matrices and official emissions. Continued implementation of the protocol will further decrease the deposition of S and N at the ICP IM sites in western and north-western parts of Europe, but in more eastern parts the decrease will be smaller (Forsius et al. 2001).

Results from the ICP IM sites were also summarised in an assessment report prepared by the Working Group on Effects of the LRTAP Convention (WGE) (Sliggers & Kakebeeke 2004, Working Group on Effects 2004).

ICP IM contributed to an assessment report on reactive nitrogen (N_r) of the WGE. This report was prepared for submission to the TF on Reactive Nitrogen and other bodies of the LRTAP Convention to show what relevant information has been collected by the ICP programmes under the aegis of the WGE to allow a better understanding of N_r effects in the ECE region. The report contributed relevant information for the revision of the Gothenburg Protocol. A revised Gothenburg Protocol was successfully finalised in 2012. A new revision process of the Protocol is currently ongoing in 2021-2023, and ICP IM is again contributing.

It should also be recognised that there are important links between N deposition and the sequestration of C in ecosystems (and thus direct links to climate change processes). These questions were studied in the CNTER-project in which data from both the ICP IM and EU/Intensive Monitoring sites were used (Gundersen et al. 2006). A summary report of the CNTER-results on C/N -interactions and nitrogen effects in European forest ecosystems was prepared for the WGE meeting 2007 (ECE/EB.AIR/WG.1/2007/10).

Trend assessments

Empirical evidence on the development of environmental effects is of central importance for the assessment of success of international emission reduction policy. In order to assess the impacts of air pollution and climate change in the environment, a long-term integrated monitoring approach in remote unmanaged areas including physical, chemical, and biological variables is needed. Vuorenmaa et al. (2018) evaluated long-term trends (1990–2015) for deposition and runoff water chemistry and fluxes, and climatic variables at 25 ICP IM sites in Europe that commonly belong also to the LTER Europe/ILTER networks. The trend assessment was published in a special issue in Science of the Total Environment with the title: "International Long-Term Ecological Research (ILTER) network". The recent results from trend assessment at IM sites confirm that emission abatement actions are having their intended effects on precipitation and runoff water chemistry in the course of successful emission reductions in different regions in Europe. Concentrations and deposition fluxes of SO_4^{2-}, and consequently acidity in precipitation, have substantially decreased in IM areas. Deposition of TIN has decreased in most of the IM areas, but to a lesser extent than that of SO_4^{2-}. Substantially decreased SO_4^{2-} deposition has resulted in decreased concentrations and output fluxes of SO_4^{2-} in runoff and decreasing trends of TIN concentrations in runoff – particularly for nitrate – are more prominent than increasing trends. In addition, decreasing trends appeared to strengthen over the course of emission reductions during the last 25 years. TIN concentrations in runoff were mainly decreasing, while trends in output fluxes were more variable, but trend slopes were decreasing rather than increasing. However, decreasing trends for S and N emissions and deposition and deposition reduction responses in runoff water chemistry tended to be more gradual since the early 2000s. Air temperature increased significantly at 61% of the sites, while trends for precipitation and runoff were rarely significant. The site-specific variation of SO_4^{2-} concentrations in runoff was most strongly explained by deposition. Climatic variables and deposition explained the variation of TIN concentrations in runoff at single sites poorly, and as yet there are no clear signs of a consistent deposition-driven or climate-driven increase in TIN exports in the catchments.

Vuorenmaa et al. (2018) reported that the IM sites are located in areas with very different N deposition, and it is obvious that not all potential drivers were included in the empirical model in the study, and further analysis with specific landscape and soil data is needed to elucidate the variation in inorganic N concentrations in runoff at IM sites.

Vuorenmaa et al. (2020) carried out a first analysis on the impact of internal catchment N-related parameters on TIN leaching. A significant negative correlation was found between the annual change of TIN concentrations and fluxes in runoff, and mean TIN fluxes in throughfall, tot N concentrations and N/P-ratios in foliage and litterfall, and tot N concentrations and fluxes in soil water. A significant positive correlation was found between the mean concentrations and fluxes of TIN in runoff and mean TIN deposition in throughfall and mean tot N concentrations and N/P-ratios in foliage and litterfall. Using multiple regression analysis, the annual change in TIN concentrations and fluxes and mean TIN concentrations and fluxes in runoff were dominantly explained by mean tot N concentrations in foliage (R^2 values 0.88–0.97). Discriminant analysis was applied with sites having significant decrease in TIN concentrations in runoff and sites having no significant decrease as the dependent dichotomy variable (classes). The foliage N/P-ratio distinguished between two trend classes, and the sites with no significant decrease exhibited higher N/P-ratio than the sites with significant decrease. Since majority of sites showed downward trend slope in TIN concentrations (76%) and fluxes (69%), these results mean that the most N-affected sites with the highest N deposition to the forest floor and highest N concentrations in foliage, litterfall, runoff water and soil water, showed the most pronounced decreases of TIN in runoff. Decrease of TIN in concentrations and fluxes in runoff was also pronounced at sites where decreasing trend of TIN in bulk deposition was highest.

Summary of earlier trend studies from IM

First results from a trend analysis of monthly ICP IM data on bulk and throughfall deposition as well as runoff water chemistry were presented in Vuorenmaa (1997). ICP IM data on water chemistry were also used for a trend analysis carried out by the ICP Waters and results were presented in the Nine-Year Report of that programme (Lükewille et al. 1997).

Calculations on the trends of N and S compounds, base cations and protons were made for 22 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^{2-}, nitrate and ammonium bulk deposition (fluxes or concentrations) were observed at 50% of the ICP IM sites. Sites with higher N deposition and lower C/N-ratios clearly showed higher N output fluxes. These results were consistent with previous observations from European forested ecosystems. Decreasing SO_4^{2-} and base cation trends in runoff waters were commonly observed at the ICP IM sites. At some sites in the Nordic countries decreasing nitrate and proton (increasing pH) were also observed. The results partly confirmed the effective implementation of emission reduction policy in Europe. However, clear responses were not observed at all sites, showing that recovery at many sensitive sites can be slow and that the response at individual sites may vary greatly.

Data from ICP IM sites were also used in a study of the long-term changes and recovery at nine calibrated catchments in Norway, Sweden, and Finland (Moldan et al. 2001, RECOVER: 2010 project). Runoff responses to the decreasing deposition trends were rapid and clear at the nine catchments. Trends at all catchments showed the same general picture as from small lakes in Fennoscandia.

It was agreed at the ICP IM Task Force meeting in 2004 that a new trend analysis should be carried out. The preliminary results were presented in Kleemola (2005) and the updated results in the 15th Annual Report (Kleemola & Forsius 2006). Statistically significant decreases in SO_4^{2-} concentrations were observed at a majority of sites in both deposition and runoff/soil water quality. Increases in ANC (acid neutralising capacity) were also commonly observed. For nitrate the situation was more complex, with fewer decreasing trends in deposition and even some increasing trends in runoff/soil water.

Results from several ICPs and EMEP were used in an assessment report on acidifying pollutants, arctic haze and acidification in the arctic region prepared for the Arctic Monitoring and Assessment Programme (AMAP, Forsius & Nyman 2006, www.amap.no). Sulphate concentrations in air showed generally decreasing trends since the 1990s. In contrast, levels of nitrate aerosol were increasing during the arctic haze season at two stations in the Canadian arctic and Alaska, indicating a decoupling between the trends in sulphur and nitrogen. Chemical monitoring data showed that lakes in the Euro-Arctic Barents region are showing regional scale recovery. Direct effects of sulphur dioxide emissions on trees, dwarf shrubs and epiphytic lichens were observed close to large smelter point sources.

A trend assessment using monthly ICP IM data (Vuorenmaa et al. 2018) was preceded by corresponding trend evaluations for the periods 1993–2006 and 1990–2013 (Vuorenmaa et al. 2009, 2016, respectively). Moreover, trends for annual input and output fluxes of SO_4^{2-} and TIN were evaluated for the period 1990–2012 (Vuorenmaa et al. 2017). These results clearly showed the regional-scale decreasing trends of SO_4^{2-} in deposition and runoff/soil water, and suggested that IM catchments have increasingly responded to the decreases in S emissions and depositions of SO_4^{2-} since the early 1990s. Decreased N emissions also resulted in decrease of TIN deposition, but to a lesser extent than that of SO_4^{2-}, and trends in TIN fluxes in runoff were highly variable due to complex processes in terrestrial catchment that are not yet fully understood. Besides, the net release of SO_4^{2-} in forested catchments fuelled by the mobilisation of legacy S pools, accumulated during times of high atmospheric sulphur deposition, may delay the recovery from acidification. The more efficient retention of inorganic N than SO_4^{2-} results in generally higher leaching fluxes of SO_4^{2-} than those of inorganic N in European forested ecosystems. Sulphate thus remains the dominant source of actual soil acidification despite the generally lower input of SO_4^{2-} than inorganic N. Critical load calculations for Europe also indicated exceedances of the N critical loads over large areas. Long-term trends for deposition and runoff variables were for the first time evaluated together with climatic variables (precipitation, runoff water volume and air temperature) at IM sites by Vuorenmaa et al. (2016). Many study sites exhibited long-term seasonal trends with a significant increase in air temperature, precipitation, and runoff particularly in spring and autumn, but annual trends were rarely significant. It was concluded that the sulphur and nitrogen problem thus clearly requires continued attention as a European air pollution issue, and further long-term monitoring and trend assessments of different ecosystem compartments and climatic variables are needed to evaluate the effects, not only of emission reduction policies, but also of changing climate.

An assessment on changes in the retention and release of S and N compounds at the ICP IM sites was prepared for the 21st Annual Report (Vuorenmaa et al. 2012). Updated and revised data were included in the continuation of the work in the 22nd and 23rdAnnual Reports. The role of organic N in mass balance budget was derived and trends of S and N in fluxes were analysed (Vuorenmaa et al. 2013, 2014).

Detected responses in biological data

The effect of pollutant deposition on natural vegetation, including both trees and understorey vegetation, is one of the central concerns in the impact assessment and prediction. Recent studies using ICP IM data on dose-response relationships showed a weak recovery of epiphytic lichen communities in Sweden despite improvements in air quality (Weldon & Grandin, 2021) and found a relationship between increasing levels of nitrogen deposition and increased dominance of nitrophyllic bryophytes in forest understory, but no effect on species richness (Weldon et al., 2022).

In 2010, the Task Force meeting decided upon a new reporting format for biological data. The new format was based on primary raw data and not aggregated mean values as before. All countries were encouraged to re-report old data in the new format. This was successful and as a result, the full potential of the biological data from the ICP Integrated Monitoring network could be utilised to raise and answer research question that the old database could not. As a direct consequence, Dirnböck et al. (2014) utilised the re-reported long-term monitoring data from 28 Integrated Monitoring sites to analyse the effect by nitrogen deposition on temporal trends in plant species cover and diversity. In many European countries airborne nitrogen coming from agriculture and fossil fuel burning exceeds critical thresholds and threatens the functioning of ecosystems. One effect is that high levels of nitrogen stimulate the growth of only a few plants that outcompete other, often rare, species. As a consequence, biodiversity declines. Though this is known to happen in natural and semi-natural grasslands, it has never been shown in forest ecosystems where management is a strong, mostly overriding determinant of biodiversity. Dirnböck et al. (2014) found that at sites where N deposition exceeded the critical load, the cover of forest plant species preferring nutrient-poor soils (oligotrophic species) significantly decreased whereas plant species preferring nutrient-rich soils (eutrophic species) showed – though weak – an opposite trend. These results show that airborne N has changed the structure and composition of forest floor vegetation in Europe. Plant species diversity did not decrease significantly within the observed period, but the majority of newly established species was found to be eutrophic. Hence it was hypothesised that without reducing N deposition below the critical load forest biodiversity will decline in the future.

Summary of earlier work on biological data from IM

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.

De Zwart (1998) carried out an exploratory analysis of possible causes underlying the aspect of forest damage at ICP IM sites, using multivariate statistics. These results suggested that coniferous defoliation, discolouration, and lifespan of needles in the diverse phenomena of forest damage are for respectively 18%, 42% and 55% explained by the combined action of ozone and acidifying S and N compounds in air.

As a separate exercise, the epiphytic lichen flora of 25 European ICP IM monitoring sites, all situated in areas remote from local air pollution sources, was statistically related to measured levels of SO_4^{2-} , ammonium nitrate and SO_2– in precipitation, annual bulk precipitation, and annual average temperature (van Herk et al. 2003, de Zwart et al. 2003). It was concluded that long distance transport of nitrogen air pollution is important in determining the occurrence of acidophytic lichen species and constitutes a threat to natural populations that is strongly underestimated so far.

Dynamic modelling and assessment of the effects of emission/deposition scenarios

In a policy-oriented framework, dynamic models are needed to explore the temporal aspect of ecosystem protection and recovery. The critical load concept, used for defining the environmental protection levels, does not reveal the time scales of recovery. Priority in the ICP IM work is given to site-specific modelling. The role of ICP IM is to provide detailed and consistent physical and chemical data and a long time-series of observations for key sites against which model performance can be assessed and key uncertainties identified (see Jenkins et al. 2003). ICP IM participates also in the work of the Joint Expert Group on Dynamic Modelling (JEG) of the WGE. Since September 2019, this expert group has reorganised into an international designated centre under the International Cooperative Programme on Modelling and Mapping, under the name Centre for Dynamic Modelling (CDM).

Dynamic vegetation modelling at ICP IM sites has been conducted with contributions from ICP M&M, ICP Forests, and the LTER Europe network. The VSD+ model was applied to simulate soil chemistry at 26 sites in ten countries throughout Europe (Holmberg & Dirnböck 2015, 2016, Dirnböck et al. 2018a, 2018b, Holmberg et al. 2018). Simulated future soil conditions improved under projected decrease in deposition and current climate conditions: higher pH, base saturation (BS), and C: N at 21, 16 and 12 of the sites, respectively. Dirnböck et al. (2018b) found, however, that a release from eutrophication is not expected to result from the decrease in N deposition under current legislation emission (CLE) reduction targets until 2030. Weldon (2024) compared modelled (VSD+/PROPS) and observed vegetation at the Swedish IM sites and found the models performed better with vascular plants than with mosses and lichens.

Dynamic models have also previously been developed and used for the emission/deposition and climate change scenario assessment at several selected ICP IM sites (e.g., Forsius et al. 1997, 1998a, 1998b, Posch et al. 1997, Jenkins et al. 2003, Futter et al. 2008, 2009). These models are flexible and can be adjusted for the assessment of alternative scenarios of policy importance. The modelling studies 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. 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 reduction, but further to promote substantial deterioration in pH status of freshwaters and other N pollution problems in some areas of Europe.

Work has also been conducted to predict potential climate change impacts on air pollution related processes at the sites. The large EU-project Euro-limpacs (2004–2009) studied the global change impacts on freshwater ecosystems. The institutes involved in the project used data collected at ICP IM and ICP Waters sites as key datasets for the modelling, time-series, and experimental work of the project. A modelling assessment on the global change impacts on acidification recovery was carried out in the project (Wright et al. 2006). The results showed that climate/global change induced changes may clearly have a large impact on future acidification recovery patterns and need to be addressed if reliable future predictions are wanted (decadal time scale). However, the relative significance of the different scenarios was largely determined by site-specific characteristics. For example, changes in sea-salt deposition were only important at coastal sites and changes in decomposition of organic matter at sites which are already nitrogen saturated.

In response to environmental concerns, the use of biomass energy has become an important mitigation strategy against climate change. A summary report on links between climate change and air pollution effects, based on results of the Euro-limpacs project, was prepared for the WGE meeting 2008 (ECE/EB.AIR/WG.1/2008/10). It was concluded that the increased use of forest harvest residues for biofuel production is predicted to have a significant negative influence on the base cation budgets causing re-acidification at the study catchments. Sustainable forestry management policies would need to consider the combined impact of air pollution and harvesting practices.

Pools and fluxes of heavy metals

The work to assess spatial and temporal trends on concentrations, stores, and fluxes of heavy metals at ICP IM sites is led by Sweden. In 26th Annual Report data on Pb, Cd, Hg, Cu and Zn from countries in the ICP IM were presented (Åkerblom & Lundin 2017). These data were used for establishment of background heavy metal concentrations in forested compartments and risk assessments of heavy metals.

The results presented by Eklöf et al. (2024) showed decreasing trends were observed in 15% (Hg), 39% (Pb) and 45% (Cd) of the watercourses during the period of evaluation. Decreasing trends were mainly observed between 2000 and 2005 for Hg and between 2000 and 2015 for Pb and Cd. For the last five years of the studied time period (2015–2020), more watercourses showed significant increasing, rather than decreasing Hg, Pb and Cd trends. This was interpreted as a legacy effect of metals still retained in catchment soils. The overall negative trends during the earlier part of the study period were likely driven by declining deposition of metals over Europe, especially for Pb and Cd.

In many national studies on ICP IM sites, detailed site-specific budget calculations of heavy metals (including Hg) have improved the scientific understanding of ecosystem processes, retention times and critical thresholds. ICP IM sites are also used for dynamic model development of these compounds. For the future evaluation of emission reductions of heavy metals to the atmosphere site-specific long-term trends for fluxes of heavy metals (primarily for Cd, Pb, and Hg and depending on availability of data, also Cu and Zn) will be analysed in deposition (input) and runoff (output), using available long-term monthly data collected across ICP IM sites in Europe. This will be done to see if fluxes of heavy metals in deposition and runoff respond to changes in emission reductions in Europe. Reduction in heavy metal emissions is hypothesised to be reflected in decreasing heavy metal concentrations (Åkerblom & Lundin 2015), taking into account climatic variation over time and between regions also in decreasing heavy metal fluxes. Temporal trend analysis in heavy metal fluxes will provide a detailed understanding of responses in heavy metal mass balances to emission reductions and give indication on possible change in retention of heavy metals in catchments over time. This overview will also provide an estimate on the significance in heavy metal mass balances over time and identify uncertainties in the mass balances and needs for improvements.

Input-output budgets of Hg help to explain the increase or no change in Hg concentrations in the upper-most forest soil mor-layer despite the general decrease in atmospheric deposition (Åkerblom & Lundin 2015). One process that is not accounted for in ICP IM programme is the land-atmosphere exchange of Hg. The phenomenon of land-atmosphere exchange has been known for a long time, but it has been quantified only recently due to the development of micrometeorological systems for continuous measurements (Osterwalder et al. 2016). In the case of mass balance calculations for Hg new evidence has shown that land-atmosphere exchange during a 2-year study over a peatland can be more than double the flux in stream runoff (Osterwalder et al. 2017). Based on natural Hg stable isotope studies in podzols and histosols, significant Hg re-emission from organic soil horizons occurred (Jiskra et al. 2015). These novel observations and knowledge about processes that govern land-atmosphere exchange of Hg calls for methods and approaches to account for this important flux in the catchment cycle of Hg within ICP IM.

The objective of the aluminium (Al) contribution of Krám and Kleemola in the 28th Annual Report (2019) was to collect and present recently available information about Al fractions from the Integrated Monitoring (IM) database and stimulate the IM National Focal Points to checkout and add not yet reported Al fractions data to the IM database for a publication in peer-reviewed journal. Al does not belong to the group of so-called heavy metals and is not transferred in large quantities by atmospheric deposition to forest catchments like most of the heavy metals. However, elevated inputs of strong acids from the anthropogenic atmospheric deposition to sensitive sites could mobilize Al from soils and stream sediments in a form of potentially toxic Al fractions to surface waters (Gensemer & Playle 1999). Different fractions of aqueous Al have very different toxicity levels for aquatic biota. Modified methods of the original Al fractionation procedure of Driscoll (1984) were applied and reported from fourteen IM catchments. Total monomeric Al (Al_m) and organic monomeric Al (Al_o, sometimes called non-labile Al) were measured in surface water by a colorimetry method. The Al_o was separated using a strong cation exchange resin, the method utilized charge exclusion by ion exchange. Potentially toxic inorganic monomeric Al (Al_i, sometimes called labile Al) was calculated as the difference between Al_m and Al_o. The ICP IM database contains relevant data about Al fractions in surface runoff from fourteen catchments so far. These catchments belong to seven countries: Finland (5), Norway (3), United Kingdom (2), Czech Republic (1), Estonia (1), Sweden (1) and Switzerland (1). Distinct patterns were evident in runoff waters of these catchments. The highest Al_i values were detected at CZ02 (median 340 µg L^{-1}) and at SE04 (median 210 µg L^{-1}). Very high Al_i concentrations were measured at NO01 and NO03 (median 170 µg L^{-1} and 130 µg L^{-1}, respectively). Slightly elevated Al_i values were documented at GB02, EE02, FI01 and FI02. The remaining IM catchments (GB01, FI03, FI04, FI05, NO02 and CH02) showed very low Al_i concentrations in runoff water. Timely inclusion of missing Al_i values from catchments with available but not reported Al_i data to the IM database is advisable (Krám & Kleemola 2019).

Summary of earlier work on heavy metals

Preliminary results on concentrations, fluxes and catchment retention were reported to the Working Group on Effects in 2001 (document EB.AIR/WG.1/2001/10). The main findings on heavy metals budgets and critical loads at ICP IM sites were presented by Bringmark (2011). Input/output budgets and catchment retention for Cd, Pb and Hg in the years 1997–2011 were determined for 14 ICP IM catchments across Europe (Bringmark et al. 2013). Litterfall plus throughfall was taken as a measure of the total deposition of Pb and Hg (wet + dry) on the basis of evidence suggesting that, for these metals, internal circulation is negligible. The same is not true for Cd. Excluding a few sites with high discharge, between 74 and 94% of the input, Pb was retained within the catchments; significant Cd retention was also observed. High losses of Pb (>1.4 mg m^{-2} yr^{-1}) and Cd (>0.15 mg m^{-2} yr^{-1}) were observed in two mountainous Central European sites with high water discharge. All other sites had outputs below or equal to 0.36 and 0.06 mg m^{-2} yr^{-1}, respectively, for the two metals. Almost complete retention of Hg, 86–99% of input, was reported in the Swedish sites. These high levels of metal retention were maintained even in the face of recent dramatic reductions in pollutant loads. In the Progress report on heavy metal trends at ICP IM sites (Åkerblom & Lundin 2015) temporal trends were seen in forest floor with decreasing concentrations for Cd and Pb while Hg did not change. An increase in heavy metal concentrations was also seen in deeper mineral soil horizon indicating a translocation of heavy metals from upper to deeper soil horizons.

Calculation of critical loads and their exceedance, relationships to effect indicators

The critical load (CL) methodology has been a key science-based tool for assessing the environmental consequences of air pollution. Critical loads are deposition thresholds used to describe the sensitivity of ecosystems to atmospheric deposition. Critical loads for eutrophication and acidification were computed using a long-term dataset of intensively studied forested ecosystem ICP Integrated Monitoring sites (n = 17) in northern and central Europe (Forsius et al. 2021). The sites belong to the ICP Integrated Monitoring and eLTER networks. The link between the site-specific calculations and time-series of CL exceedances and measured site data was evaluated using long-term measurements (1990–2017) for bulk deposition, throughfall and runoff water chemistry. Novel techniques for presenting exceedances of CLs and their temporal development were also developed. Concentrations and fluxes of SO_4^{2-}, TIN and acidity in deposition substantially decreased at the sites. Decreases in S deposition resulted in statistically significant decreased concentrations and fluxes of sulphate in runoff and decreasing trends of TIN in runoff were more common than increasing trends. The temporal developments of the exceedance of the CLs indicated the more effective reductions of S deposition compared to N at the sites. There was a relation between calculated exceedance of the CLs and measured runoff water concentrations and fluxes, and most sites with higher CL exceedances showed larger decreases in both TIN and proton concentrations and fluxes. Sites with higher cumulative exceedance of eutrophication CLs (averaged over 3 and 30 years) generally showed higher TIN concentrations in runoff. The results provided evidence on the link between CL exceedances and empirical impacts, increasing confidence in the methodology used for the European-scale CL calculations. The results also confirm that emission abatement actions are having their intended effects on CL exceedances and ecosystem impacts.

In Holmberg et al. (2013) empirical impact indicators of acidification and eutrophication were determined from stream water chemistry and runoff observations at ICP IM catchments. The indicators were compared with exceedances of critical loads of acidification and eutrophication obtained with deposition estimates for the year 2000. Empirical impact indicators agreed well with the calculated exceedances. Annual mean fluxes and concentrations of acid neutralising capacity (ANC) were negatively correlated with the exceedance of critical loads of acidification. Observed leaching of nitrogen was positively correlated with the exceedances of critical loads (Holmberg et al. 2013). This study was revisited with new data on N concentrations and fluxes (Holmberg et al. 2017). For most sites, there was an improvement visible as a shift towards less exceedance and lower concentrations of TIN in runoff. At most of the sites both the input and the output flux of TIN decreased between the two observation periods 2000–2002 and 2013–2015. Data from the ICP IM provide evidence of a connection between modelled critical loads and empirical monitoring results for acidification parameters and nutrient N.

Planned activities

- Maintenance and development of central ICP IM database at Swedish Agricultural University (SLU).
- Continued assessment of the long-term effects of air pollutants to support the implementation of emission reduction protocols, including:
  - Assessment of trends.
  - Calculation of ecosystem budgets, empirical deposition thresholds and site-specific critical loads.
  - Dynamic modelling and scenario assessment.
  - Comparison of calculated critical load exceedances with observed ecosystem effects.
- Calculation of pools and fluxes of heavy metals at selected sites.
- Assessment of cause-effect relationships for biological data, particularly vegetation.
- Coordination of work and cooperation with other ICPs, particularly regarding dynamic modelling (all ICPs), cause-effect relationships in terrestrial systems (ICP Forests, ICP Vegetation), and surface waters (ICP Waters).

- Cooperation with other external organisations and programmes, particularly the European and International Long Term Ecological Research Network (ILTER, www.ilter.network, Mirtl et al. 2018).
- Participation in projects with a global change perspective.

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ICP IM activities, monitoring sites and available data

Review of the ICP IM activities from June 2024 to June 2025

Meetings

- Salar Valinia, Ulf Grandin, and James Weldon represented ICP IM at the Tenth Joint Session of the Working Group on Effects and the Steering Body to EMEP, held in Geneva 9–13 September 2024.
- James Weldon represented ICP IM at the joint meeting of EMEP Steering Body and Working Group on Effects Extended Bureau, held in Ljubljana 25 -26 March 2025.
- James Weldon represented ICP IM and gave an online presentation about current activities, at the CDM/CCE/M&M meeting, held in Helsinki, Finland 18-20 February 2025.
- The thirty-third meeting of the Programme Task Force on ICP Integrated Monitoring was held in Dessau, Germany (and online), 23–25 April 2025.
- James Weldon represented ICP IM and gave an online presentation about current activities, at the ICP Forests Task Force meeting, held in Dresden, Germany, 19-23 May 2025.

Data issues

The National Focal Points (NFPs) reported their results to the ICP IM Programme Centre. The Programme Centre carried out standard check-up of the results and incorporated them into the IM database.

Scientific work and activities in priority topics

- Dynamic modelling using new EMEP deposition scenarios as part of ex-post analysis
- A scientific paper on Hg and heavy metal trends in concentrations across ICP Integrated Monitoring sites in Europe (Eklöf et al.) was published (2024).

Activities and tasks planned for 2025–2026

ICP IM activities on the WGE 2024–25 work plan, current status in italics:

- Scientific paper on the effects from deposition on vegetation community stability over time (2025). *On track for publication 2025.*

- Scientific paper on trends in heavy metal fluxes across ICP Integrated Monitoring sites (2026)

- An assessment of the mercury data gathered by the newly installed passive samplers (2025/6). *This is currently delayed due to funding and personnel issues at the Canadian EPA who are co-ordinators for the sampling campaign*

- As far as possible, making the ICP IM database accessible, under a "by attribution" licence, and aiming to meet FAIR principles, and by publishing a data paper to explain the IM monitoring infrastructure in more detail (2025). *On track for publication 2025.*

- Scientific paper or report - Update in long-term changes in the atmospheric deposition and runoff water chemistry of sulfate, inorganic nitrogen and acidity. *Included in this report.*

- Initiate a revision and update of the IM manual. An ad-hoc group will provide recommendations to the TF meeting in an ongoing process that will extend to the next work plan (2024-25). *BI subprogramme revised, new taxonomy for all subprogrammes dealing with species developed. Next focus will be Meteorology and an update of some methods for chemical analysis, as agreed at TF meeting 2025.*

- Proof of concept for development of above ground vegetation monitoring in ICP IM sites using drone remote sensing (2025). Subject to external funding being approved. *This was not obtained, and this item will not proceed.*

Other activities

- Maintenance and development of central ICP IM database at Swedish Agricultural University (SLU).
- Arrangement of the 33rd Task Force meeting (2025).
- Preparation of the 34th ICP IM Annual Report (2025).
- Preparation of the ICP IM contribution to assessment reports of the WGE
- Participation in meetings of the WGE and other ICPs

Published reports and articles 2022–2024

Evaluations of international ICP IM data and related publications

Eklöf, K. *et al.* (2024) 'Trends in mercury, lead and cadmium concentrations in 27 European streams and rivers: 2000-2020', *Environmental pollution.* https://doi.org/10.1016/j.envpol.2024.124761.

Weldon, J., Merder, J., Ferretti, M., Grandin, U. (2022). Nitrogen deposition causes eutrophication in bryophyte communities in central and northern European forests. Annals of Forest Science 79(24). doi: 10.1186/s13595-022-01148-6

Evaluations of national ICP IM data and publications of ICP IM representatives

Monteith, D. T., Henrys, P. A., Hruška, J., de Wit, H. A., Krám, P., Moldan, F., . . . Evans, C. D. (2023). Long-term rise in riverine dissolved organic carbon concentration is predicted by electrolyte solubility theory. Science Advances, 9(3), eade3491. doi:10.1126/sciadv.ade3491

Liptzin, D., Boy, J., Campbell, J.L., Clarke, N., Laclauf, J.-P., Godoy, R., Johnson, S.L., Kaiser, K., Likens, G.E., Pihl Karlsson, G., Markewitz, D., Rogora, M., Sebestyen, S.D., Shanley, J.B., Vanguelova, E., Verstraeten, A., Wilcker, W., Worralls, F., McDowell, W.H. (2022). Spatial and Temporal Patterns in Atmospheric Deposition of Dissolved Organic Carbon. Global Biogeochemical Cycles, doi: 10.1029/2022GB007393.

Monteith D.T., Henrys P.A., Hruška J., de Wit H.A., Krám P., Moldan F., Posch M., Raike A., Stoddard J.L., Shilland E.M., Gloria Pereira M., Evans C.D. (2023) Long-term rise in riverine dissolved organic carbon concentration is predicted by lectrolyte solubility theory. *Science Advances*, 9(3): eade3491, 1-11.

Petrash D.A., Krám P., Pérez-Rivera K.X., Buzek F., Čuřík J., Veselovský F., Novák M. (2023) Soil solution data from Bohemian headwater catchments record atmospheric metal deposition and legacy pollution. *Environmental Science and Pollution Research*, doi.org/10.1007s11356-023-25673-7.

Yttri, K. E., Canonaco, F., Eckhardt, S., Evangeliou, N., Fiebig, M., Gundersen, H., Hjellbrekke, A.-G., Lund Myhre, C., Platt, S. M., Prévôt, A. S. H., Simpson, D., Solberg, S., Surratt, J., Tørseth, K., Uggerud, H., Vadset, M., Wan, X., and Aas, W.: Trends, composition, and sources of carbonaceous aerosol at the Birkenes Observatory, northern Europe, 2001–2018, Atmos. Chem. Phys., 21, 7149–7170, https://doi.org/10.5194/acp-21-7149-2021, 2021.

Reports:
Austnes, K., Hjermann, D.O., Sample, J.E., Wright, R.F., Kaste, O., de Wit, H. 2022. Nitrogen in surface waters: time trends and geographical patterns explained by deposition levels and catchment characteristics. NIVA-rapport 7728-2022. ICP Waters report 149-2022.

Weldon, J. "Modelling Forest biodiversity and recovery from acidification", Report 2024:2 (Uppsala, Department of Aquatic Sciences and Assessment of the Swedish University of Agricultural Sciences, 2024).

Monitoring sites and data

The following countries have continued data submission to the ICP IM database during the period 2016–2024: Austria, Belarus, the Czech Republic, Estonia, Finland, Germany, Ireland, Italy, Lithuania, Norway, Poland, the Russian Federation, Spain, Sweden, and Switzerland.

The number of sites with on-going data submission for at least part of the data years 2015–2024 is 48 from fifteen countries. Sites from Canada, Latvia and the United Kingdom only contain older data.

An overview of the data reported internationally to the ICP IM database is given in Table 1. Some additional reported data from non-active sites may be available, please contact the PC if you want more information. Locations of the ICP IM monitoring sites are shown in Fig. 1.

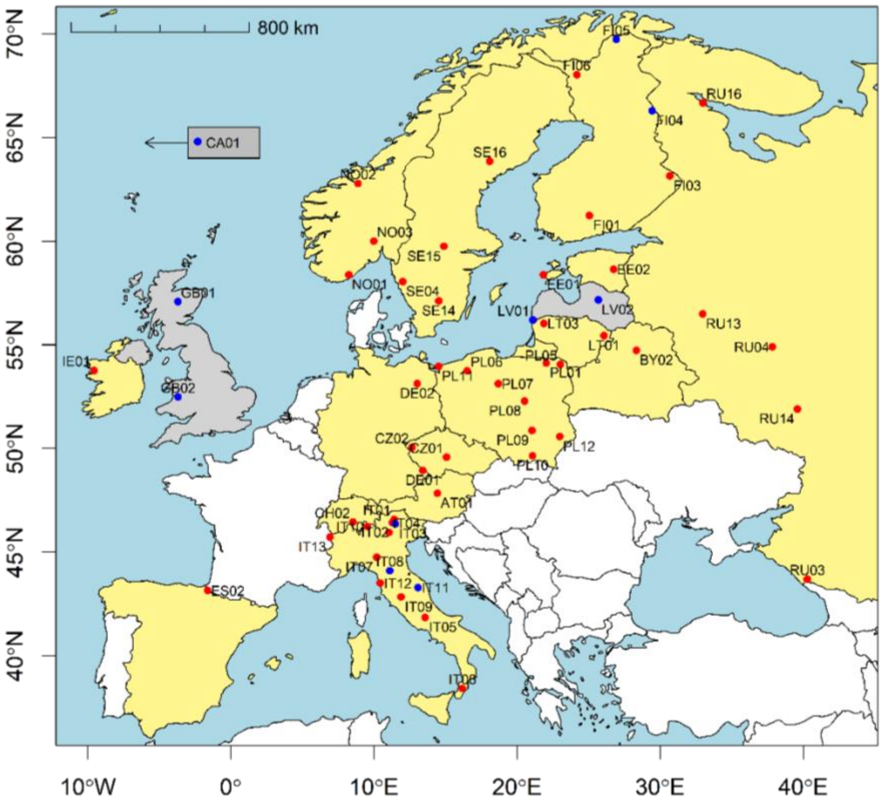

Figure 1: Location and status of ICP IM sites. For site names, see Table 1. Red mark: active site. Blue mark: non-active site. Yellow: country with active IM sites. Grey: country with only non-active sites.

*Table 1. Internationally reported data from ICP IM sites (- subprogramme not possible to carry out, * or forest health parameters in former Forest stands/Trees).*

AREA	SUBPROGRAMME																							
	AM	AC	PC	MC	TF	SF	SC	SW	GW	RW	LC	FC	LF	RB	LB	* FD	VG	BI	VS	EP	AL	MB	BB	BV
	meteorology	air chemistry	precipitation chemistry	moss chemistry	throughfall	stemflow	soil chemistry	soil water chemistry	groundwater chemistry	runoff water chemistry	lake water chemistry	foliage chemistry	litterfall	hydrobiology of streams	hydrobiology of lakes	forest damage	vegetation	bioelements	vegetation structure	trunk epiphytes	aerial green algae	microbial decomposition	bird inventory	vegetation inventory
AT01 ZÖBELBODEN	95-23	95-23	93-23		93-23	99-04	04	93-23		95-23		92-23	93-23				93			93-98				
BY02 BEREZINA BR	89-15	89-15	89-15				95-98			95-15														
CH02 LAGO NERO	15-19	15-19	15-19				18	17-19		15-19	15-16						17							
CZ01 ANENSKE POVODI	89-23	89-22	89-23	89	89-23		02-20	07-23	08-22	89-23				07										
CZ02 LYSINA	67-20	93-96	90-23		91-23		93	90-23	89-23	89-23	91-23	94	08	07	11		15	94			14-15		10	
DE01 FORELLENBACH	90-23	90-23	90-23	90	90-23	90-05	90-11	90-23	88-23	90-23		90-23	90-22			90-14	90-08		00	92-95		94-23	91-02	90-95
DE02 NEUGLOBSOW	67-23	98-23	98-23		98-23	04-23	04-16	98-23	98-23		98-23	06-23	04-23			23	04-24					22		
EE01 VILSANDI	95-23	94-23	94-23	94-20	94-23	94-23	94-20	94-23	95-96			94-23	94-23			94-17	94-21			94-21		94-23		94
EE02 SAAREJÄRVE	94-23	98-23	94-23	94-21	94-23	94-23	94-20	95-23	95-21	94-23	96	94-23	94-23			96-17	96-22	12		94-21	94-17	94-23	98-14	
ES02 BERTIZ	08-17	08-23	07-23		07-23	08-19	10-15	07-18		07-22		08-23	08-23			07-12	07-21		07					
FI01 VALKEA-KOTINEN	88-23	94-20	88-23	88-96	89-17	89-99	88-89	89-17		88-23	87-23	88-17	90-16		90-93	88-91	88-09			88-97		90	87-89	87
FI03 HIETAJÄRVI	88-23	93-00	88-23	89-96	89-17	89-99	88	89-17	93-23	88-23	87-23	88-17	90-16		90	88-91	90-09			90-97		90-91	87-89	
FI06 PALLASJÄRVI	13-23		14-23		16-17			02-17	18-23	04-23	04-23	95-17	07-16										88-89	
IE01 BRACKLOON WOOD			91-16		91-11	92-97		91-16				91-96	91-98											
IT01 RENON-RITTEN	90-19	93-19	93-14		93-13	93-13	93-11	93-13		00-13		93-10	00			92-13	09		05-09	92		93-11		
IT03 PASSO LAVAZE	92-21	93-22	92-13		94-13	94-00	93-95	95-07		01-13		93-05	94			93-19	95-09		99-09	92				
IT05 SELVA PIANA	97-21	97-22	97-19		97-19	97-19	95	02-08				97-19				97-19	09		99-09					
IT06 PIANO LIMINA	99-19	97-16	97-23		97-23	97-21	95	19-23				97-19				97-19	09		99-09					
IT07 CARREGA	97-21	97-22	97-23		97-23	97-00	95	19-23		98-13		97-19				97-19	09		99-09					
IT09 MONTE RUFENO	97-21	97-22	97-23		97-23	97-00	95	02-23		97-14		97-19				97-19	09		99-09					
IT10 VAL MASINO	97-19	00-15	97-15		97-15		95	05-07				97-05				97-09	09		99-09					
IT11 ROTI		97-22	97-12		97-12		95					97-05				97-09	09		99-09					
IT12 COLOGNOLE	97-01	97-15	97-15		97-15	97-00	95					97-05				97-09	09		99-09					
IT13 LA THUILE	97-21	97-15	09-15		09-15		95					97-05				97-09			99-08					
LT01 AUKSTAITIJA	93-13	93-19	93-19	93-20	93-19		93-20	94-23	93-23	93-23		06-23	99-23	12-20		00-23	93-23	20	02-23	93-23	93-23			93
LT03 ZEMAITIJA	90-13	95-19	95-19	06-20	95-19		94-20	95-23	95-23	95-23		06-23	99-23	95-20		00-22	94-23	20	02-23	94-23	94-23			94
NO01 BIRKENES	87-21	87-23	87-23	92	89-23		87-11	86-23	87-88	87-23		86-17	87-02			91-18	86-18			86				
NO02 KÅRVATN	87-91	87-23	87-23	88	89-11		89-13	89-10		87-23		89-09	89-02			92-10	89-09							
NO03 LANGTJERN		87-97	77-23		86-03		91-13	91-03		87-23		86-03	87-02											
PL01 PUSZCZA BORECKA	06-23	16-23	16-23		16-23	21-23	17	10-23			16-23		06-23				16-23							
PL05 WIGRY	06-23	16-23	16-23		16-23	21-23	19	06-23		16-23			05-23				16-23							
PL06 PARSENTA	10-23	16-23	94-23		96-23	21-23		10-23		94-23			10-23				23							
PL07 POJEZIERZE CHELMINSK	16-23	16-23	16-23				18	20		16-23							23							
PL08 KAMPINOS	09-23	16-23	16-23		16-23	21-23	16	12-19		21-23			10-23				16-23							
PL09 LYSOGORY	05-23	16-23	16-23		16-23	21-23		05-23		16-23			05-23				16-23							
PL10 BESKIDY	94-23	16-23	94-23		02-23	21-23		11-23		94-23			09-23				16-23							
PL11 WOLIN	16-23	16-23	16-23		17-23	21-23	21	16-23		16-23			16-23				23							
PL12 ROZTOCZE	16-23	16-23	16-23		16-23	21-23	23	16-23		16-23			16-23				16-23							
PL13 POZNAN-MORASKO	22-23	22-23	22-23		22-23	22-23				22-23			22-23				23							
PL14 KARKONOSZE	23	23	23		22-23	22-23		22-23		22-23			22-23				23							
RU03 CAUCASUS BR	89-94	89-23	89-98																					
RU04 OKA-TERRACE BR	89-06	89-23	89-98	90										93-99		93-23	93-02			93		94-96		
RU12 ASTRAKHAN BR	93-94	93-21	93-94																					
RU13 CENTRAL FOREST BR	93	93-94	93													09-23	18-20							
RU14 VORONEZH BR	94	94-23	94-98																					
RU16 VELIKIY ISLAND				89-90			89	89	89						93-99	93-23	91-94			89-94	93	94-95		91
RU47 KURSK																18-21								
RU48 MOSCOW ARBORETUM																19-23								
SE04 GÅRDSJÖN F1	87-23	88-23	87-23	95	87-23		95-10	96-23	79-23	87-23		99-23	96-23			97-01	95-22	91-20	91-20	96-21	92-23	99-23		
SE14 ANEBODA	96-23	96-23	96-23	95	96-23		96-11	99-23	96-23	96-23		99-23	99-23			97-01	82-22	96-22	06-22	97-22	97-23	99-23		
SE15 KINDLA	97-23	96-23	96-23		96-23		97-12	99-23	97-23	96-23		97-23	99-23			98-01	96-23	98-23	98-23	98-23	97-23	99-23		
SE16 GAMMTRATTEN	99-23	99-23	99-23		99-23		00-18	00-23	00-23	99-23		99-23	00-23			00-01	99-22	99-19	99-19	00-20	00-23	00-23		

National Focal Points (NFPs) and contact persons for ICP IM sites

AT / Austria
NFP:
Johannes Kobler and Gisela Pröll
Environment Agency Austria
Spittelauer Lände 5
A-1090 Vienna
AUSTRIA
e-mail:
johannes.kobler@umweltbundesamt.at
Gisela.Proell@umweltbundesamt.at

BY / Belarus
NFP:
Anatoly Srybny
Berezinsky Biosphere Reserve
P. O Domzheritzy
Lepel District
Vitebskaya oblast, 211188
BELARUS
e-mail: srybny@vitb.pogoda.by

CZ / Czech Republic
NFP:
Adéla Holubová
Czech Hydrometeorological Institute
Košetice Observatory
CZ-394 22 Košetice
CZECH REPUBLIC
e-mail: adela.holubova@chmi.cz

Contact for site CZ02:
Pavel Krám
Czech Geological Survey
Department of Geochemistry
Klarov 3
CZ-118 21 Prague 1
CZECH REPUBLIC
e-mail: pavel.kram@geology.cz

CH / Switzerland
NFP:
Luca Colombo and Fabio Lepori
Institute of Earth Sciences
University of Applied Sciences and Arts of Southern Switzerland, SUPSI
Campus Trevano, 6952 Canobbio
SWITZERLAND
e-mail: luca.colombo@supsi.ch
fabio.lepori@supsi.ch

DE / Germany
NFP:
Thomas Scheuschner
Federal Environment Agency
Air Pollution and Terrestrial Ecosystems
Wörlitzer Platz 1
D-06844 Dessau-Roßlau
GERMANY
e-mail: thomas.scheuschner@uba.de

Contact for site DE01:
Angelika Kölbl
Nationalparkverwaltung Bayerischer Wald
Sachgebiet Forschung und Dokumentation

Integriertes Ökosystemmonitoring
Freyunger Straße 2
D-94481 Grafenau
GERMANY
e-mail: angelika.koelbl@npv-bw.bayern.de

Contact for site DE02:
Nicole Wellbrock
Thünen Institute
Alfred-Möller-Straße 1,
Haus 41/42, 16225
Eberswalde,
GERMANY
e-mail: icp-neuglobsow@thuenen.de

EE / Estonia
NFP:
Heidi Koger
Ambient Air Department,
Ministry of Climate,
Suur-Ameerika 1,10122 Tallinn,
ESTONIA
e-mail: heidi.koger@kliimaministeerium.ee

Kairi Lõhmus
Estonian Environmental Research Centre

Marja 4d, 10617 Tallinn,
ESTONIA
e-mail: kairi.lohmus@klab.ee

ES / Spain

NFP:
Jesús Miguel Santamaría and
David Elustondo
Laboratorio Integrado de Calidad Ambiental,
LICA
Departamento de Química y Edafología
Universidad de Navarra
Irunlarrea 1, 31008 Pamplona
SPAIN
e-mail: chusmi@unav.es
delusto@unav.es

FI / Finland

Contact persons:
Martin Forsius and Jussi Vuorenmaa
Finnish Environment Institute, SYKE
Latokartanonkaari 11
FI-00790 Helsinki
FINLAND
e-mail: martin.forsius@syke.fi
jussi.vuorenmaa@syke.fi

IE / Ireland

NFP:
Thomas Cummins
University College Dublin
UCD School of Agriculture and
Food Science
Belfield, Dublin 4
IRELAND
e-mail: thomas.cummins@ucd.ie

IT / Italy

NFP:
Giancarlo Papitto
Comando Unità Tutela Forestale,
Ambientale e Agroalimentare Carabinieri
Ufficio Studi e Progetti
Via Giosuè Carducci 5
I-00187 Rome
ITALY
e-mail: giancarlo.papitto@carabinieri.it

LT / Lithuania

Contact for sites LT01, LT03:
Algirdas Augustaitis
Vytautas Magnus University
Agricultural Academy
Faculty of Forest Sciences and Ecology
Studentu 13
LT-53362 Kaunas dstr.
LITHUANIA
email: algirdas.augustaitis@vdu.lt

NO / Norway

NFP:
Heleen de Wit
Norwegian Institute for Water Research,
Gaustadalléen 21
NO-0349 Oslo
NORWAY
e-mail: heleen.de.wit@niva.no

PL / Poland

Contact for sites PL06, PL10:
Krzysztof Skotak
Institute of Environmental Protection
National Research Institute
ul. Kolektorska 4
01-692 Warsaw
POLAND
e-mail: krzysztof.skotak@ios.edu.pl

RU / Russia

NFP:
Anna Koukhta
Institute of Global Climate and Ecology
Glebovskaya str. 20 B
107258 Moscow
RUSSIA
e-mail: anna_koukhta@mail.ru

SE / Sweden NFP: Pernilla Rönnback
Swedish University of Agricultural Sciences, SLU
Department of Aquatic Sciences and
Assessment
P.O. Box 7050 SE-75007 Uppsala
SWEDEN
e-mail: pernilla.ronnback@slu.se

Forest Disturbance and Carbon Dynamics: A Study from Southern Sweden

Madelene Söderberg[1]

[1]*Student at Kristianstad University, Sweden*

The following text is a short summary of a BSc thesis undertaken *at* Kristianstad University in co-operation with vegetation ecologists at the Swedish IM programme. The summary focus on the results that readers of the Annual Report are likely to find most relevant. The original text is in Swedish and includes an extensive discussion of multifunctional landscape perspectives and the challenges of providing potentially conflicting ecosystem services, as well as full references. Any errors in this translated summary are the editor's rather than the author's.

Introduction

Forests serve multiple functions in modern society, from biodiversity conservation and recreation to timber produciton and societal welfare, while simultaneously acting as carbon sinks to mitigate climate change and global warming. The demands and expectations placed on forests are not always entirely reasonable. Dead wood has become increasingly discussed in recent decades as a forest component that can arise naturally from various causes or be created by human activities. While individual dead trees are common, larger events such as storms or insect outbreaks can destroy parts of or entire forest stands, creating substantial amounts of dead wood. Such disturbances negatively impact both the forest sector and climate. From a production perspective, disturbances often represent major economic losses, and dead wood is viewed as a source of pests, leading to rapid removal from production forests. However, from a conservation perspective, dead wood has proven necessary for saving numerous red-listed species, and conservation focussed stakeholders therefore prefer to preserve as much dead wood as possible.

Recent research has increasingly focused on dead wood's role in climate issues. When large numbers of trees are affected by disturbances, this impacts forest carbon turnover, which can influence national carbon dioxide emissions that countries have committed to limiting under EU directives. This study examines carbon turnover after an extensive bark beetle infestation that followed a windfall event in 2005, at the Swedish Integrated Monitoring siteAneboda in south central Sweden. The overarching focus centres on these two disturbances that affected Aneboda forest between 2005-2009, and their impact on tree and carbon balance dynamics. The study aims to place dead wood in a broader landscape ecological perspective, integrating various advantages and disadvantages of larger dead wood quantities while weighing different aspects against each other.

Study Area and Background

Aneboda IM

Aneboda IM is located within a Natura 2000 area in Kronoberg County, Växjö municipality, where integrated environmental monitoring within natural ecosystems has been conducted since the 1980s. The monitoring area covers 18.9 hectares and includes systematically placed circular plots with 10-meter radii distributed throughout the area using a grid system. Within these circles, inventories have been conducted every five years since 1996, with additional inventories in 2008 and 2009 due to extensive spruce bark beetle attacks.

Forest Disturbances

In January 2005, southern Sweden was struck by storm Gudrun, which caused extensive forest damage. Approximately 75 million cubic meters of forest fell during the storm, with Kronoberg County among the most severely affected areas, losing nearly six years' worth of harvest in a single event. While production forests require rapid cleanup and replanting according to law, many reserves allowed dead trees to remain as part of natural development processes. Following Gudrun, the area was predictably affected by spruce bark beetles, which typically colonize fresh dead wood within the first three years after disturbance. These secondary attacks often cause more tree mortality than the original storm damage. The Aneboda area was not cleared after Gudrun, consistent with the nature reserve's management plan for natural forest development, resulting in extensive bark beetle infestations in subsequent years.

Methods and Results

Living and Dead Wood Volume and Carbon Calculations

Data from multiple inventory years were analyzed to calculate living and dead wood volume and carbon storage. Biomass calculations used established functions from Marklund (1988) for different tree species and components. Tree heights were estimated through regression analysis where direct measurements were unavailable. Volume calculations employed functions from Brandel (1994), with adjustments made for different categories of dead wood including logs, snags, and stumps. Carbon storage calculations required density estimates derived from biomass-to-volume ratios and carbon fraction values from the literature (Bergh, Egnell & Lundmark, 2020). The study accounted for decomposition effects over time using established decay classifications and rates (Jonsson, 2000; Neumann, Echeverria & Hasenauer, 2023).

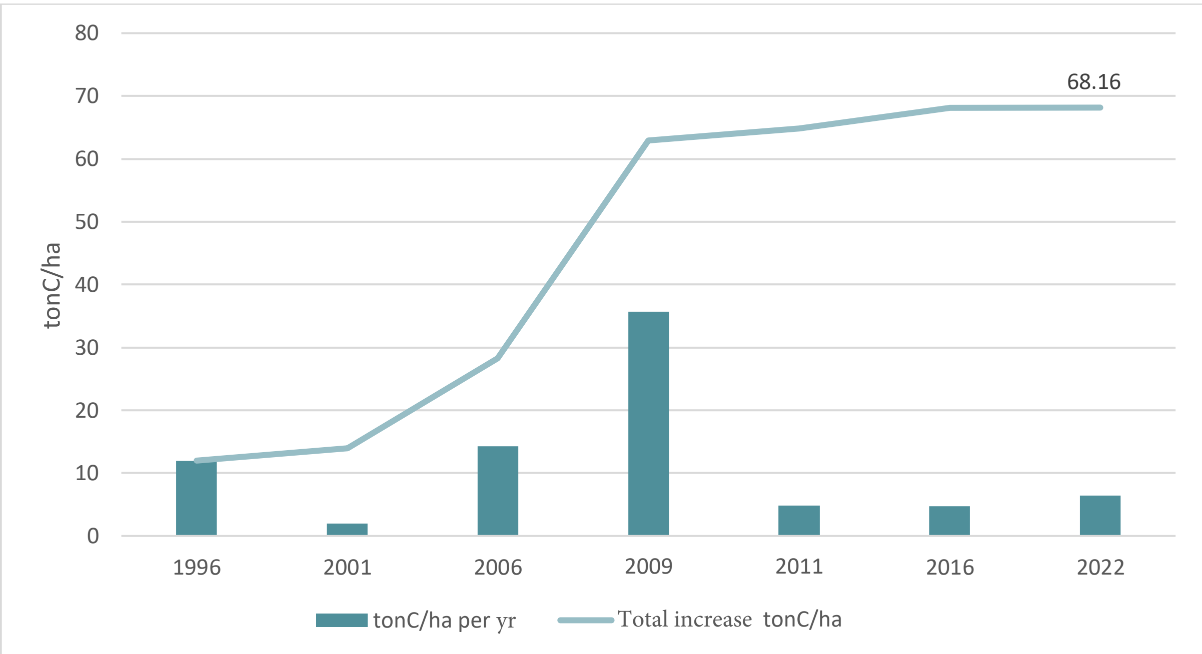

Figure 2:The bars represent the newly added amount of carbon (tons per hectare) in dead wood since the last inventory. The line shows the total amount of tons of carbon per hectare stored in dead wood, including estimated losses in the form of decomposition

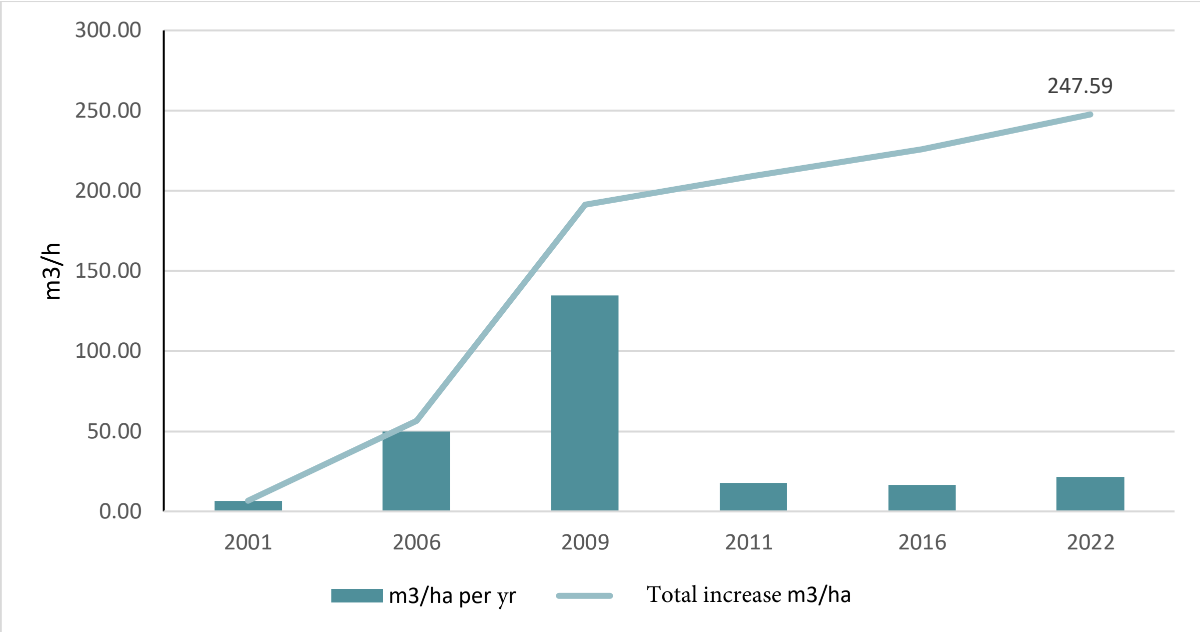

Figure 3:The bars show newly added dead wood since the last inventory The line shows the total volume of carbon/ha stored in dead wood including estimated losses in the form of decomposition

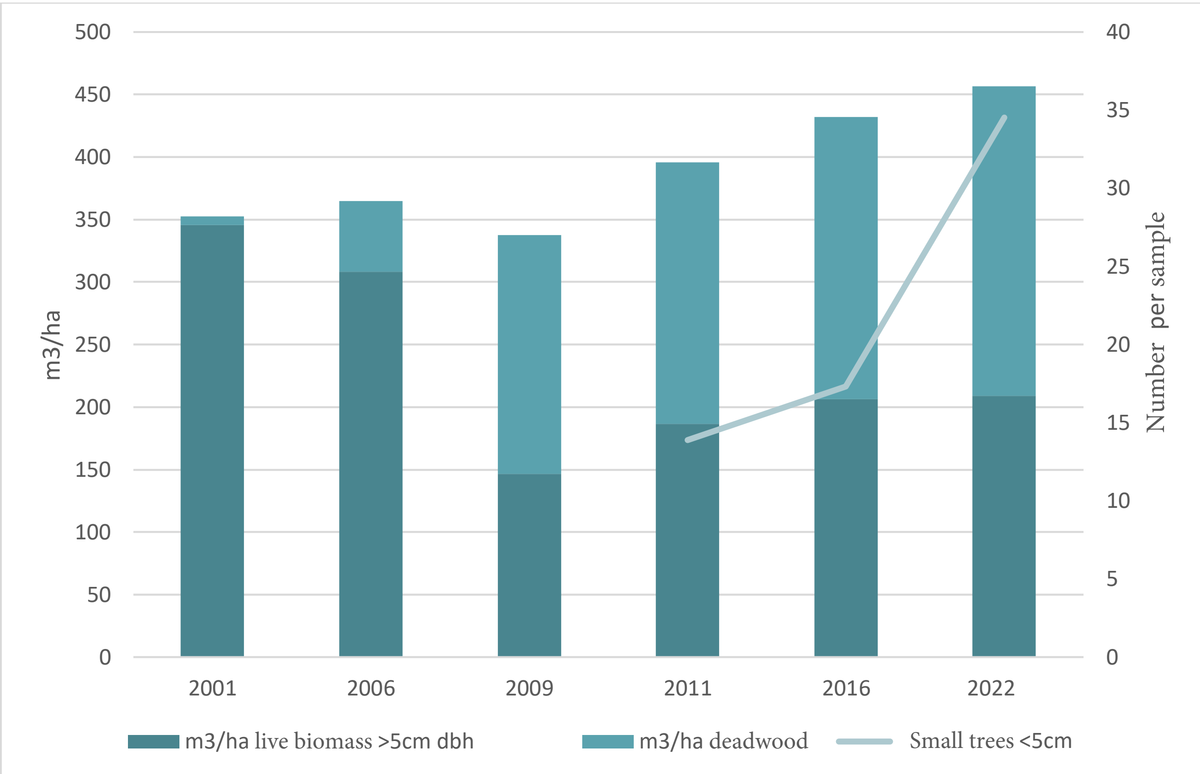

Figure 4: The plot shows the relationship between the volume of living trees (dark bars) and dead wood (light bars). The extra inventory in 2009 only included spruce, with no data on living biomass for pine and deciduous trees, hence the dip. Solid line shows small trees (<5cm dbh) as average number per sample (right hand y-axis), which shows an increase during regrowth of the forest (many birch and beech as well as spruce)

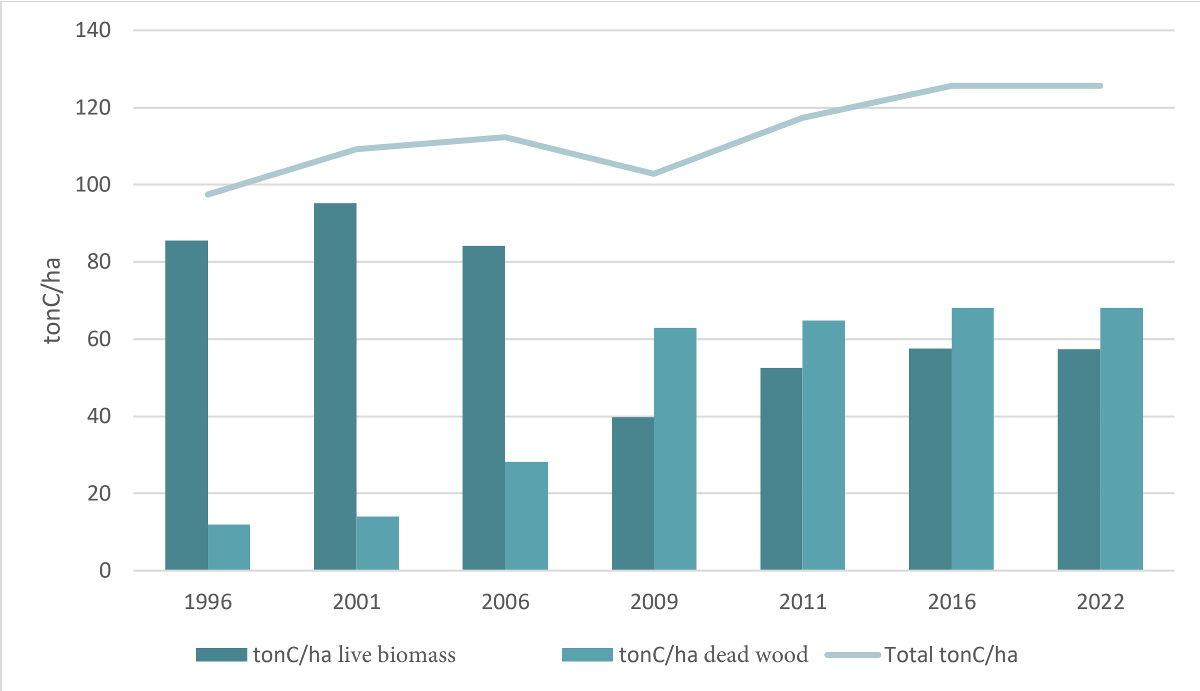

Figure 5:The plot shows the ratio of stored carbon in living biomass (dark bars) to dead wood (light bars). The solid line shows the total amount of above ground stored carbon in Aneboda. The extra inventory in 2009 only included spruce and lacks data on living biomass for pine and deciduous trees

Carbon Dynamics Over Time

The analysis revealed dramatic changes in carbon storage patterns following the disturbances. Following storm Gudrun in 2005, dead wood volume increased substantially by 2006, with an estimated 14.27 additional tons of carbon per hectare in newly dead trees (Fig.2). The most significant increase occurred by 2009, when bark beetle attacks had killed an additional 252 trees per hectare, primarily spruce. This resulted in an estimated 35.67 tons of carbon per hectare in the 2009 cohort of dead trees alone (Fig. 1). By 2022, total dead wood volume reached 247.58 cubic meters per hectare, with total carbon storage in dead wood estimated at 68.16 tons per hectare (Fig. 3).

Living Biomass Changes

The disturbances dramatically altered the balance between living and dead biomass carbon storage. Before 2005, the forest maintained typical carbon storage patterns with most carbon held in living trees. Following the disturbances, dead wood became the dominant carbon pool, fundamentally changing ecosystem carbon dynamics. Living biomass showed gradual recovery over time, with increasing numbers of small trees establishing in the post-disturbance environment. However, by 2022, living tree volume remained substantially below pre-disturbance levels, indicating slow ecosystem recovery typical of such severe disturbances (Fig. 3, Fig. 4).

Conclusions

The Aneboda case study demonstrates the profound impacts that sequential disturbances can have on forest carbon dynamics. Storm Gudrun and subsequent bark beetle attacks fundamentally altered carbon storage patterns, converting the forest from a carbon sink dominated by living biomass to a system with massive dead wood carbon pools. The estimated 68.16 tons of carbon per hectare stored in dead wood by 2022 represents an extraordinary accumulation that will influence ecosystem processes for decades. This is a very unusual situation for Sweden - a mixed age semi-natural forest including many large old trees killed by bark beetles being left to naturally regenerate, with all dead wood remaining in place. Total carbon remained on a stable trend despite disturbances (so far).

These results highlight the complexity of managing forests for multiple objectives simultaneously. While Aneboda's extensive dead wood accumulation poses challenges for recreation and represents lost timber revenue, it provides exceptional biodiversity habitat and research opportunities. The area serves specialized conservation goals within a broader landscape matrix where other areas can prioritize different functions.

Rather than attempting to optimize multifunctionality within individual forest stands, the Aneboda example suggests benefits of landscape-level functional specialization. By allowing one area to accumulate extensive dead wood for conservation and research purposes, surrounding production forests can operate with lower dead wood levels while still contributing to landscape-scale multifunctionality. The carbon implications remain complex, with dead wood serving as both a delayed carbon source through decomposition and a carbon storage mechanism that prevented rapid emissions that would have occurred with immediate biofuel use. Forest recovery through natural regeneration will eventually restore carbon sink capacity, though this process requires decades rather than years.

Dead wood management decisions cannot be made in isolation but must consider broader landscape contexts, management objectives, and temporal scales. Effective landscape planning requires comprehensive understanding of ecological processes, economic constraints, and social values to balance competing demands on forest resources appropriately.

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Trends in sulfate, inorganic nitrogen and pH in precipitation chemistry, throughfall chemistry and runoff water chemistry since 2000

James Weldon[1]

[1] Swedish University of Agricultural Sciences (SLU), Department of Aquatic Sciences and Assessment, Box 7050, SE–750 07 Uppsala, Sweden

Introduction

Over the past four decades, coordinated European emission control policies have markedly lowered emissions and atmospheric deposition of acidifying and eutrophying pollutants, a trend consistently documented by long-term monitoring networks across Europe. Reductions have been especially strong for sulphur: sulphate deposition has decreased very substantially since monitoring began, reflecting early and sustained action in the power and industrial sectors, and reductions have continued since 2000 (Aas et al. 2024). Emissions of NOx also declined since 2000, but further reductions are still required to meet commitments and protect ecosystems. However NH_3 emissions since 2000 have decreased only slightly (Aas et al. 2024), and in some countries have increased, making NH_3 reduction a persistent challenge for meeting national emission-reduction commitments and biodiversity targets given its major contribution to eutrophication. These trends in emissions are of course reflected in changes in deposition of these pollutants at ICP IM monitoring sites (Vuorenmaa et al. 2018), and here we present an update in trends in concentrations.

Data overview

The focus for this study were the subprogrammes PC (precipitation chemistry), TF (throughfall chemistry) and RW (runoff water chemistry). For full details of the methodology please refer to the ICP Integrated Monitoring manual (ICP IM, 2022). Over time, monitoring sites have both begun and ceased operations within the IM network, and there are substantial gaps in coverage (see Fig. 1). Some of the gaps may be due to sites having data that have not yet been reported to the IM Programme Centre, and we encourage all sites to submit data that appears to be missing from the database if available. Given these gaps, the criterium for including a site in this study was that at least 10 years of data were available in the period after (and including) the year 2000. Note that this does not necessarily mean that all variables have this much data, as some of the parameters in each of the subprogrammes have lower coverage than others.

Sea salt correction was performed according to the correction factors given in the IM Manual (International Cooperative Programme on Integrated Monitoring of Air Pollution Effects on Ecosystems 2022), as sulphate values are reported as uncorrected sulphur - not sea-salt corrected anthropogenic sulphur. Corrected values for Ca, Mg and SO4S are used here and are given with the prefix “x”, e.g. xSO4S.

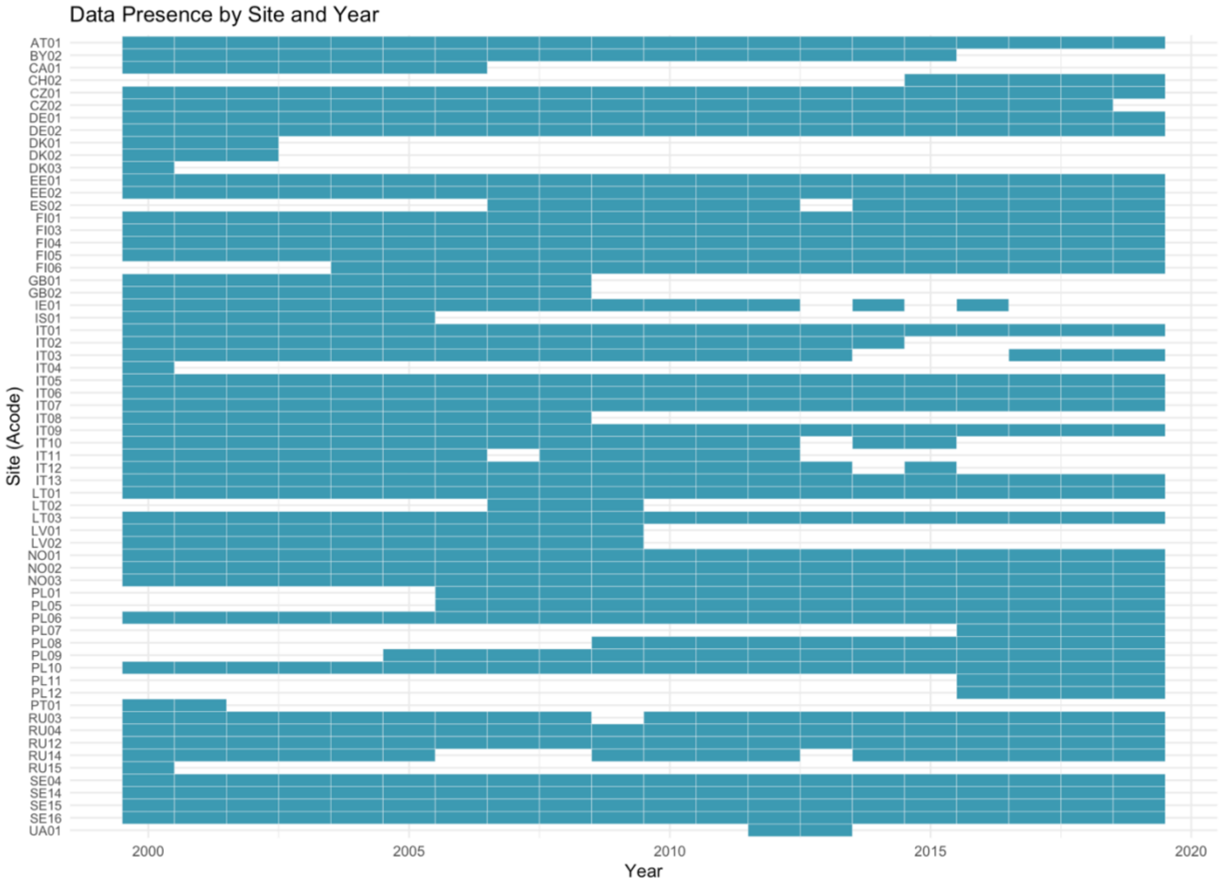

Figure 1: Overview of data coverage in the Programme Centre database of the PC, TF and RW subprogrammes of ICP Integrated Monitoring. Absences do not necessarily mean no data exist - NFPs may have access to data that have not been submitted to the central database and note that there are also submitted data from 2020 and onwards that are in the process of being added to the database.

Methods

Trends in environmental time series data are often analysed with Mann-Kendall tests and Sen-Theil slopes, which are robust and well established methods. However these can be very dependent on the time period chosen for the analysis and can hide shorter term trends, e.g. an initial increasing trend followed by a decreasing trend will likely give non-significant results over the whole time series. Generalized additive models and mixed models (GAMs/GAMMs; (Buja, Hastie, and Tibshirani 1989; Simon N. Wood 2017) can be more flexible and can be used to model time series data without assuming the shape of the trend (i.e. they are able to model non-linear responses). These have been adapted into a convenient set of functions for analysing data of the kind gathered by the IM monitoring programme, as described in the paper "A toolbox for visualizing trends in large-scale environmental data" (von Brömssen et al. 2021) and the accompanying GitHub repository with R code. These methods were used in a recent study of trends in heavy metal concentrations based partly on IM data (Eklöf et al. 2024).

For full details of the statistical approach, see von Brömssen et al. (2021), but in short the generalised additive models are fitted with the R package mgcv (S. N. Wood 2011) and derivatives and confidence intervals with the R package gratia (Simpson 2024). The R function screeningmodeling() (von Brömssen et al. 2021) is used to fit the models (calling mgcv and gratia), where seasonal variation is estimated as a cyclic cubic regression spline, and autocorrelation in the error term is estimated by a continuous autoregressive process of order 1.

A generalised additive model is fitted to the time series, where the rate of change at any time is the first derivative of the fitted smooth. Uncertainty in the derivative comes from the fitted model's variance–covariance matrix for the smooth's coefficients, using this, the model forms confidence intervals for the derivative over time. At each time, a check is performed of whether the derivative's confidence interval excludes zero: entirely above zero means a significant increase, entirely below zero means a significant decrease, and includes zero means no significant change. Contiguous spans of time with derivative confidence intervals (CIs) consistently above (or below) zero are recorded as significant periods of change. Instead of testing for differences in mean levels between arbitrary windows, this method asks where the rate of change is non-zero, which pinpoints the timing of accelerations and decelerations with uncertainty accounted for across the entire smooth trend. In short: fit the smooth, compute the derivative, get its confidence interval, mark times where zero is excluded as significant change, and finally group adjacent times to form periods.

Results

Throughfall chemistry

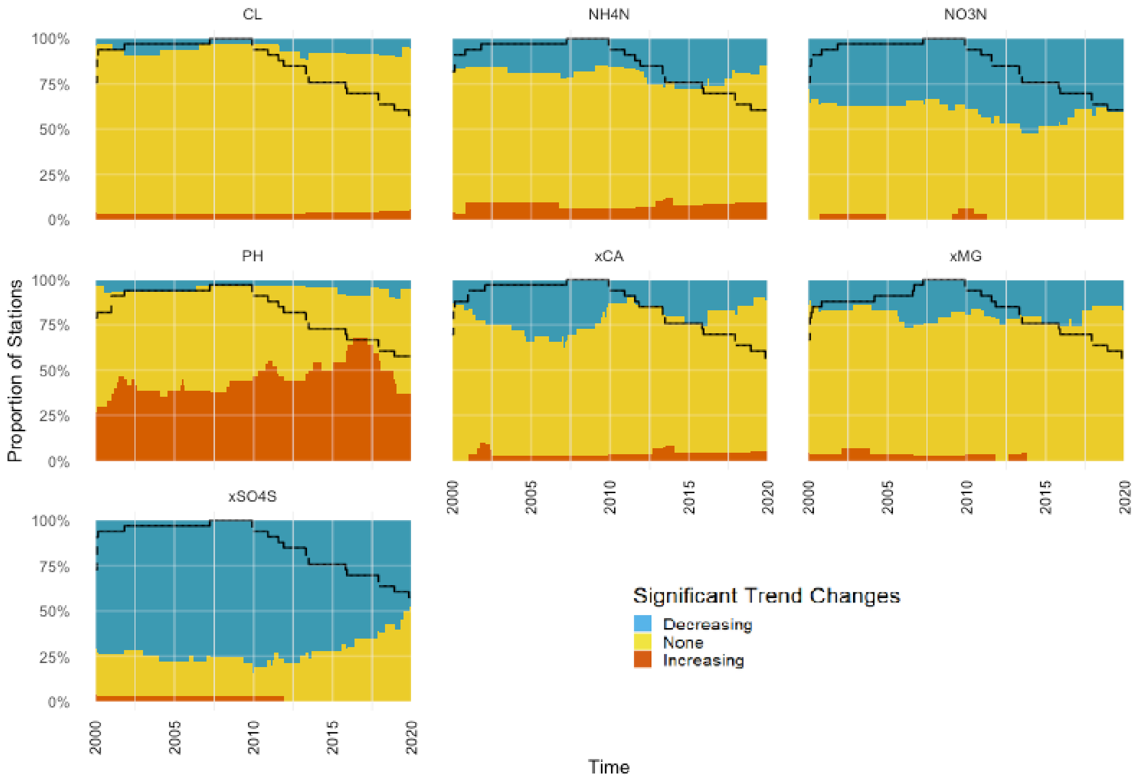

Figure 2: Proportion of sites with significant trends in throughfall chemistry. The black line indicates the proportion of sites with data for that year

For throughfall chemistry, there are many more sites showing a significantly decreasing trend in sea salt corrected SO4-S than increases, and a corresponding increasing trend in pH values at many sites (Fig. 2). There are few sites and periods with increasing NO3N and NH4N, although a majority of sites show no trend rather than significant decreases. It is clear that reduced N concentrations are more evident for NO3N than for NH4N (Fig. 2).

As there is a drop in the proportion of sites contributing data towards the end of the time series (see black line in Fig. 2 for example), as a quality control the same plot was produced using only those sites which have data for at least 95% of the time series (Fig. 3). The same general patterns are seen here, which suggests for example that the drop in proportion of sites with a decreasing trend in sea salt corrected SO4S towards the end of the time series is a real phenomenon and not a result of data availability issues. The same check was performed on throughfall (TF) and runoff water (RW) trends (however these plots are not reproduced here since, as in the TF case, the 95% proportion plots are extremely similar to the all-data plots, indicating that changes in proportions seen are not a result of changes in data availability).

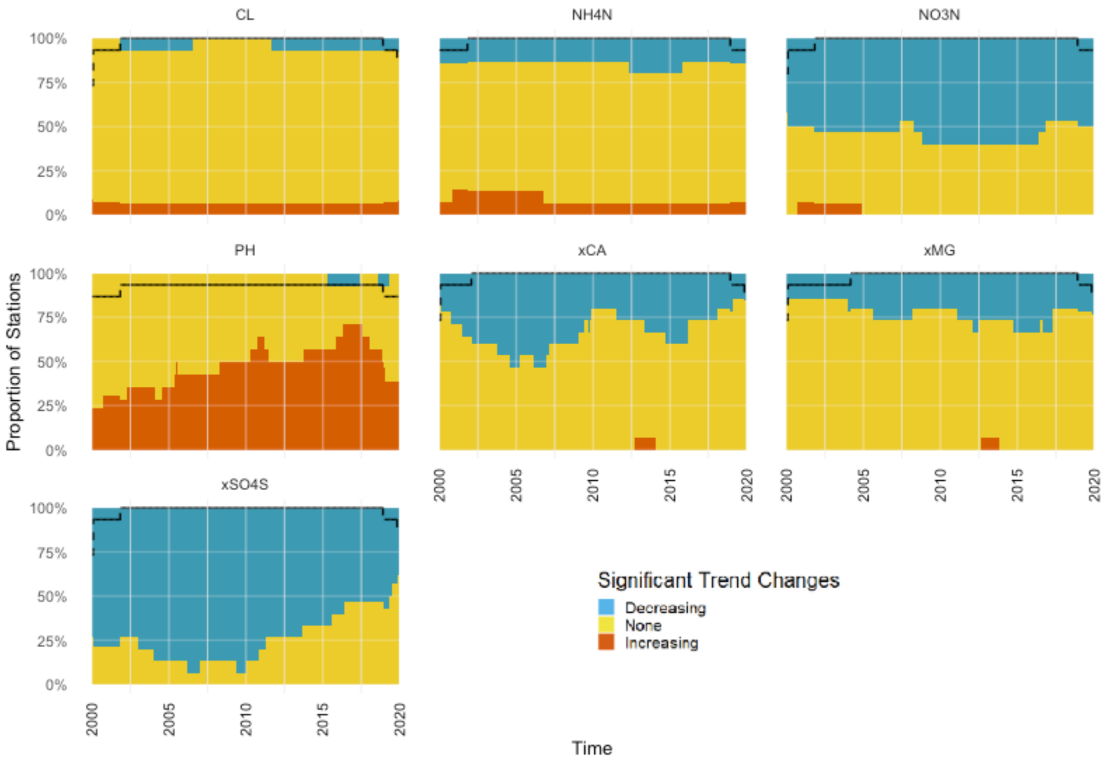

Figure 3: Proportion of sites with significant trends in throughfall chemistry. The black line indicates the proportion of sites with data for that year. Unlike in the previous figure, sites are here only included if they have data for at least 95% of the time series for xSO4S.

A more detailed view of the time series for individual sites can be seen in Fig, 4. Here the colour gradient indicates increasing trends and significance levels (orange to red as the p-value becomes smaller) and decreasing trends and significance levels (orange to blue as the p-value becomes smaller). The decreasing trends in sea salt corrected SO4S are widespread, although somewhat concentrated in the first half of the time series, with corresponding increasing trends in pH across most of the network - site specific short term trends are clearly visible in many cases, although in others there is a consistent trend over the whole time series.

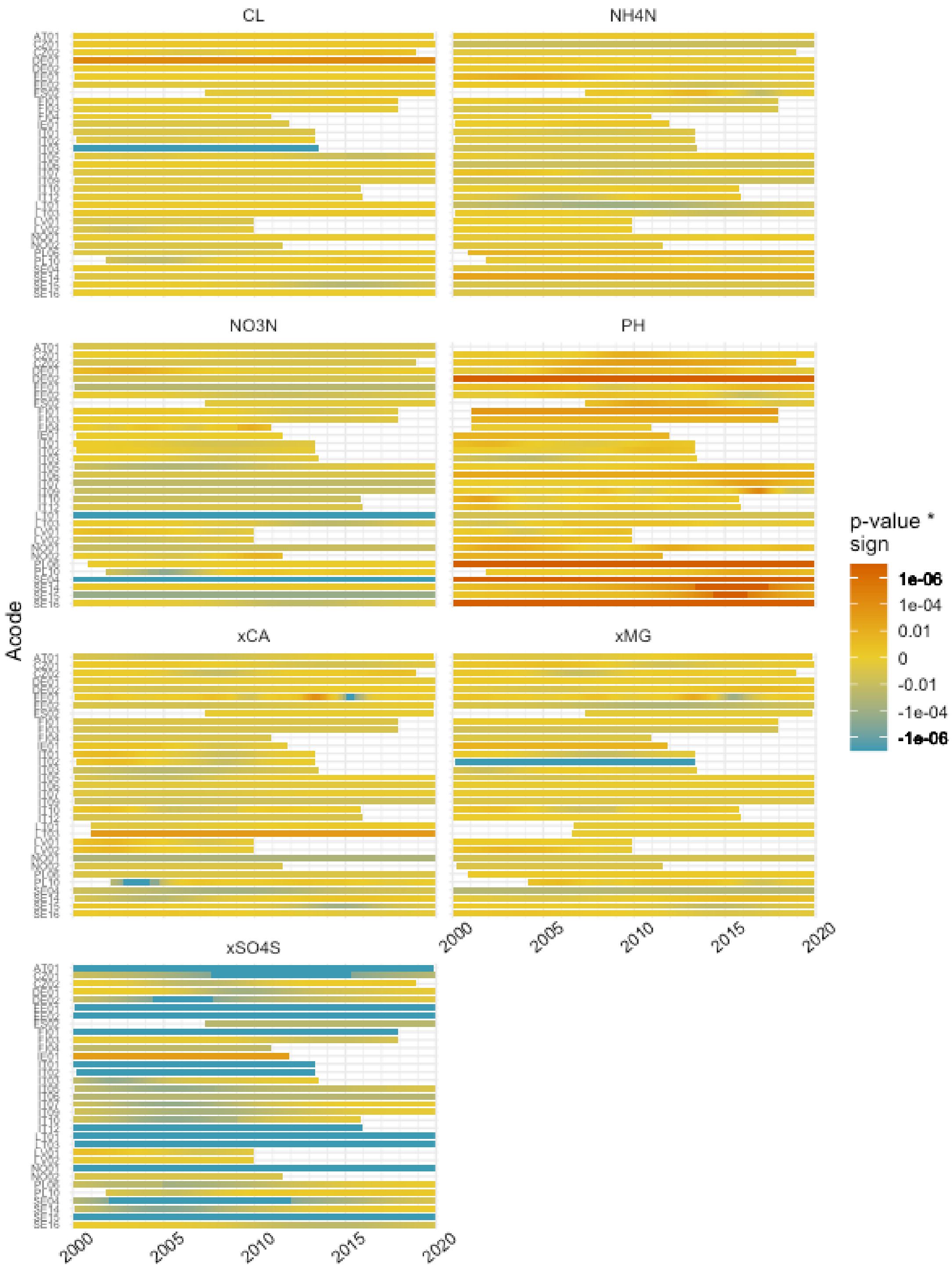

Figure 4: Trends in throughfall chemistry. The colour gradient towards red indicates an increasing trend with progressively smaller p-values, while the gradient towards blue is the equivalent for decreasing trends

Precipitation chemistry

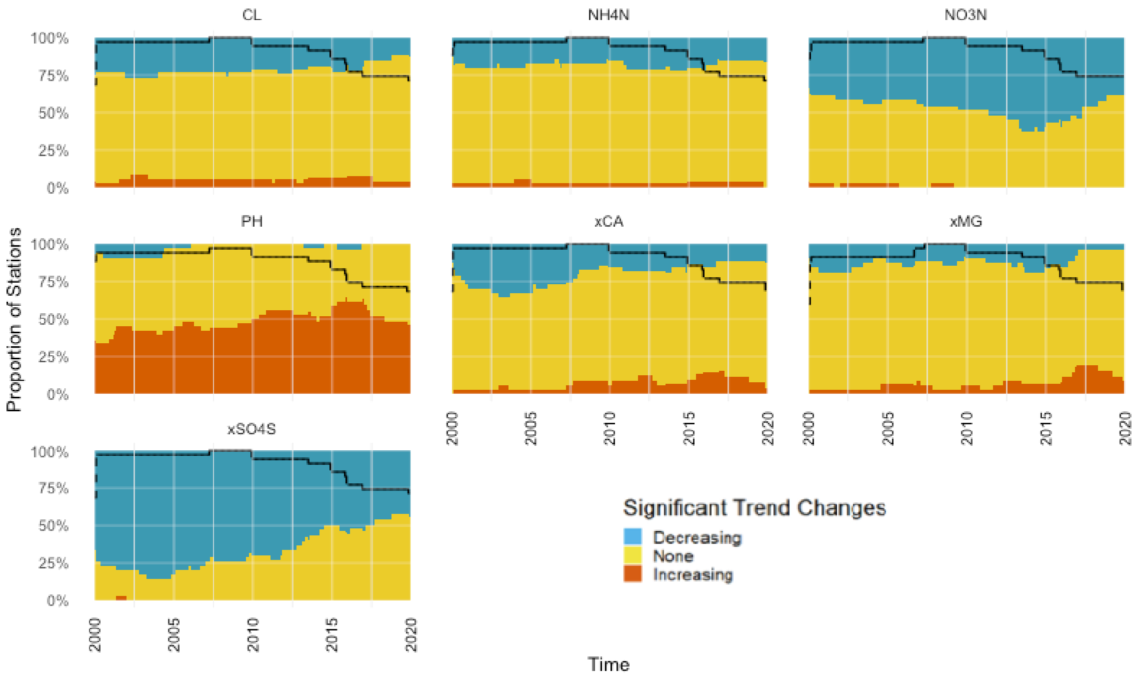

Figure 5:Proportion of sites with significant trends in precipitation chemistry. The black line indicates the proportion of sites with data for that year

In precipitation chemistry (PC), there are many more sites showing a significantly decreasing trend in sea salt corrected SO4S than increases, and a corresponding increasing trend in pH values at many sites (Fig. 5). Towards the end of the time series there is an overall shift from decreasing trend to no trend, indicating that improvements have begun to level off across the network as a whole. There are only a few sites and periods with increasing NO3N and NH4N, although a majority of sites show no trend rather than significant decreases. It is clear that reduced N concentrations are more evident for NO3N than for NH4N. Comparing the two, NO3N has a greater proportion of sites with a decreasing trend and only very few with an increasing trend, and these in the first half of the time series.

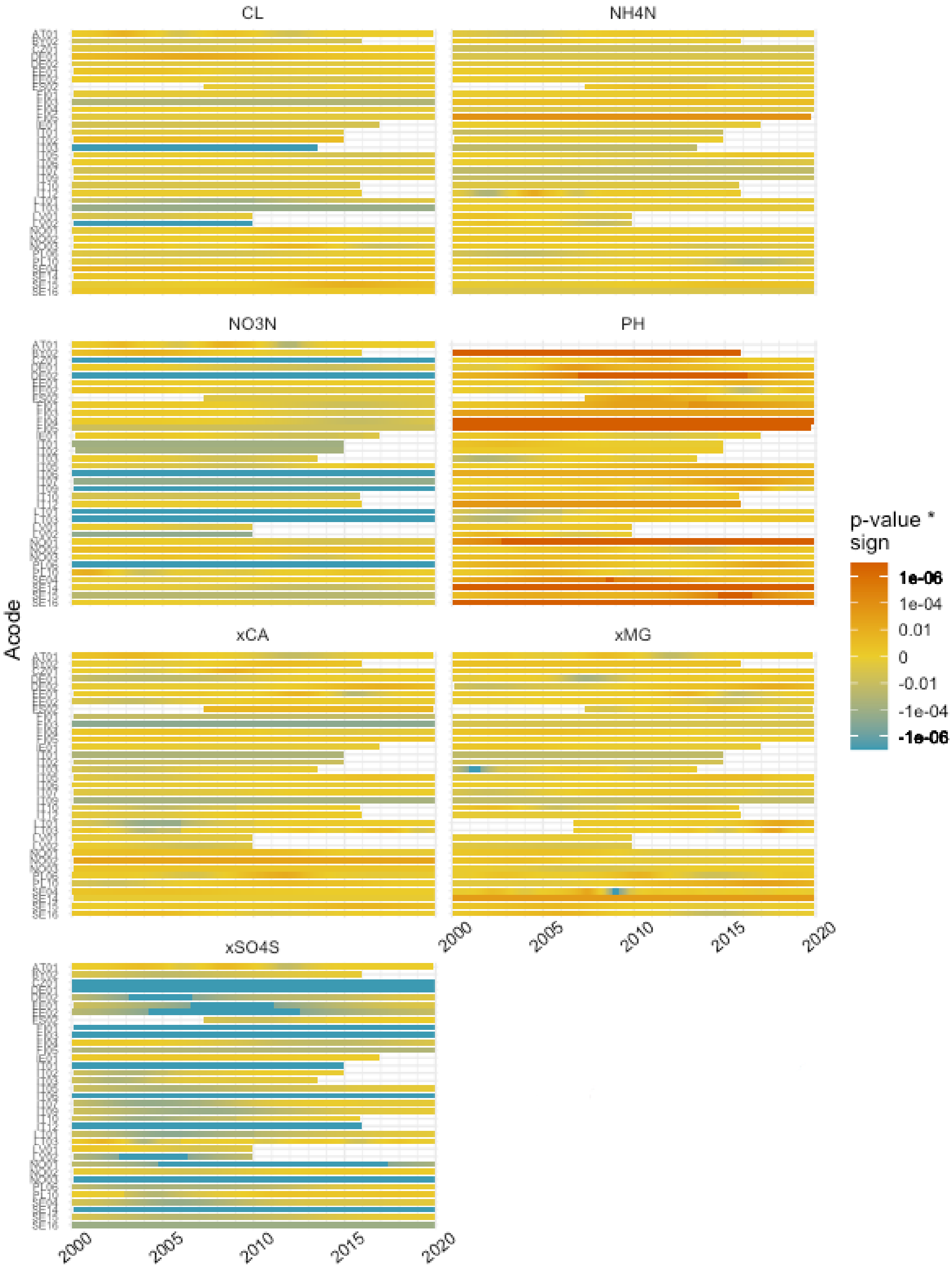

Figure 6: Trends in precipitation chemistry. The colour gradient towards red indicates an increasing trend with progressively smaller p-values, while the gradient towards blue is the equivalent for decreasing trends

Runoff water chemistry

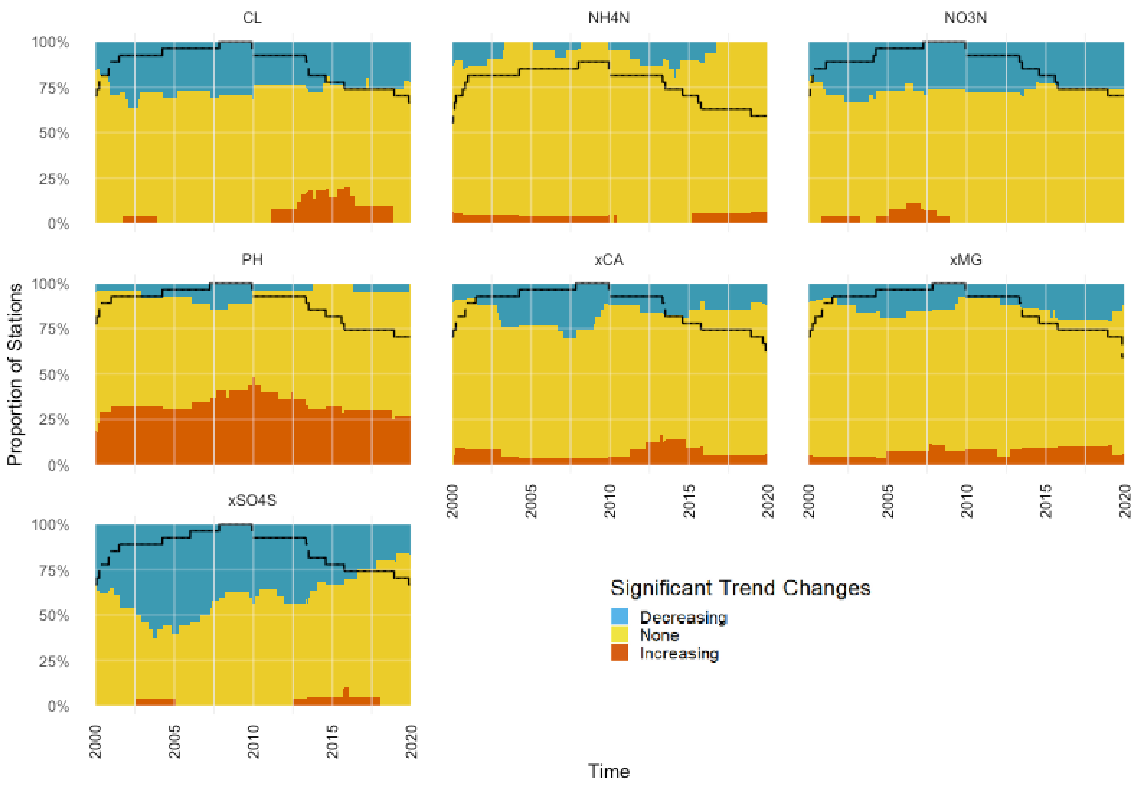

Figure 7: Proportion of sites with significant trends in runoff water chemistry. The black line indicates the proportion of sites with data for that year

For runoff water chemistry, across the key parameters of interest there are many more sites showing a significantly decreasing trend in sea salt corrected SO4S than increases, and a corresponding increasing trend in pH values at many sites (Fig. 7). A larger proportion of sites show decreasing sea salt corrected SO4S concentrations and increasing pH earlier in the time series, with an increase in sites with no trend in more recent years. As with TF and PC, there are only a few sites and periods with increasing NO3N and NH4N. However there are also few that show decreases in NH4N, with a large majority having no trend. For NO3N the picture is somewhat more positive, with only a few sites with increasing concentrations and those early in the time series, and a steady ca 25% of sites with decreasing trends.

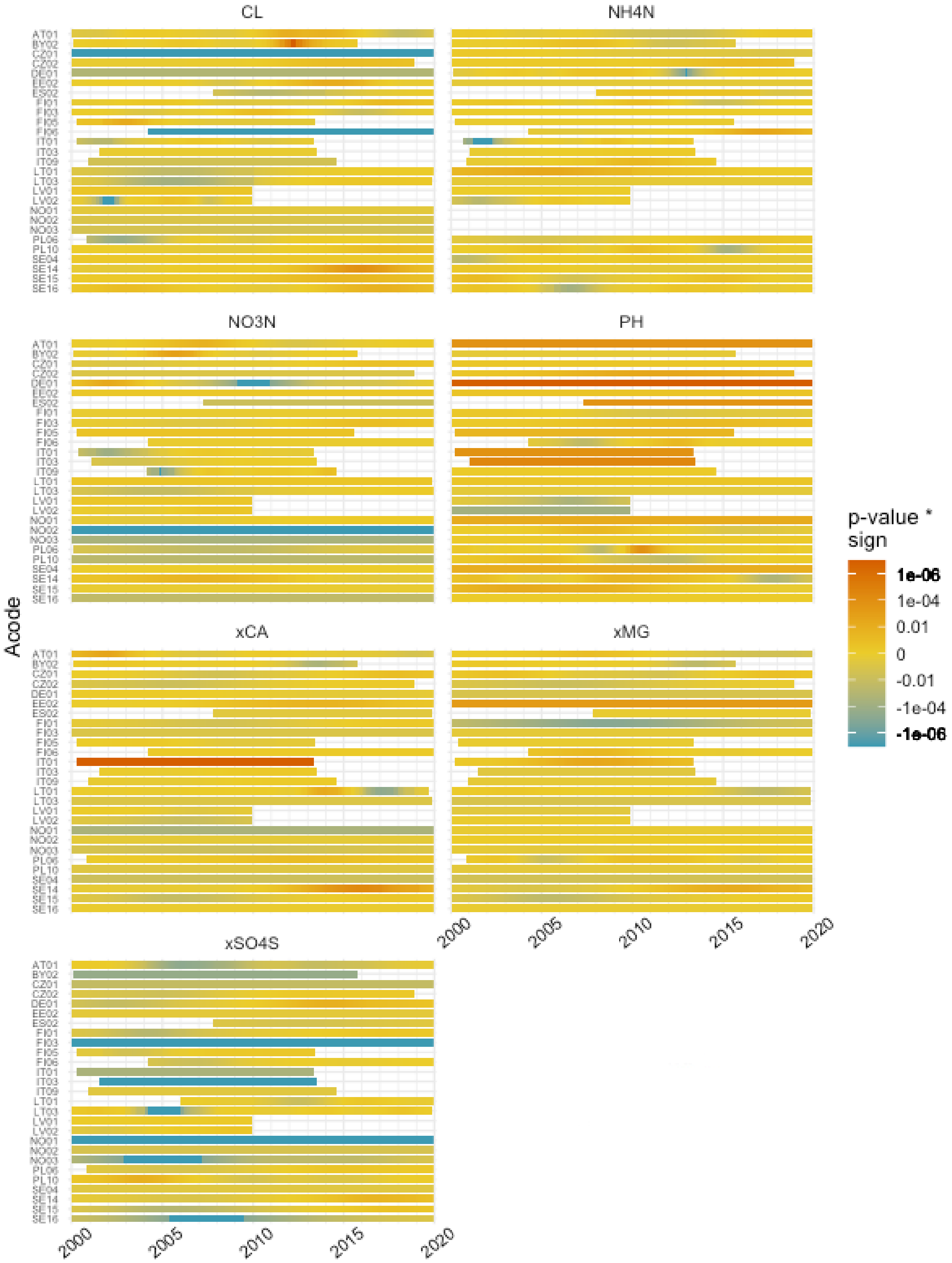

Figure 8:Trends in runoff water chemistry. The colour gradient towards red indicates an increasing trend with progressively smaller p-values, while the gradient towards blue is the equivalent for decreasing trends

Conclusions

Across all three subprogrammes (throughfall chemistry, precipitation chemistry and runoff water chemistry) there is a common general pattern of decreasing trends in sulfate concentrations and corresponding increases in pH across a majority of the IM sites in this time period. However these improvements begin to level off towards the end of the time series, with more sites showing no trend. This corresponds with a decline in the number of sites where more recent data are available, but the same pattern can be seen when limiting the analysis to sites which cover at least 95% of the period (Fig. 2, Fig. 3), so this does not explain the change. While at first sight this may seem concerning, it may also be an indication of (some) sites recovering from acidification and reaching a state close to only natural acidification occurring, where few further improvements should be expected. For N the trends are less positive than for S. Although many more sites have decreasing nitrate concentrations than increasing, and where increases are found they are always early in the time series, there are in all subprogrammes more sites with no trend than is the case for sulfate. Ammonium on the other hand shows very little change across the time series – while there are always more sites with decreasing than increasing trends, sites with no trend predominate, and the proportions (of increasing, decreasing and no trend) are rather stable over time. The trends in concentrations seen here reflect, as expected, the corresponding trends in emissions and deposition - sulphur emissions decreased substantially from 1990 until the early 2000s, followed by a consistent but more gradual decrease, and emissions of NOx also experienced a gradual decrease since the early 2000s. Emission reduction measures have been less successful for nitrogen than sulphur, and especially emissions of NH_3 have remained at problematically high levels.

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National activity reports

The following reports of national activities were received - many thanks to all those who contributed, and we look forward to a wider coverage of the network in the next issue, especially from those countries who have not sent an update for a while.

Report on National ICP IM activities in Austria

Thomas Dirnböck[1], Johannes Kobler[1], Ika Djukic[1], Sarah Venier[1], Gisela Pröll[1]

[1]*Austria Umweltbundesamt, Spittelauer Lände 5, 1090 Vienna, Austria*
National Focal Point: gisela.proell@umweltbundesamt.at, johannes.kobler@umweltbundesamt.at,

The only ICP Integrated Monitoring station in Austria, Zöbelboden, was established in the year 1992 in the northern part of the National Park Kalkalpen at 550 to 956 m.a.s.l. Beside ICP IM, the site also hosts air pollution monitoring in the framework of EMEP and is part of the Austrian EU NEC directive sites network. Apart from reporting to the ICP Integrated Monitoring (IM) Programme, the data and metadata is publicly available at the DEIMS-SDR portal (https://deims.org/8eda49e9-1f4e-4f3e-b58e-e0bb25dc32a6) and/or the B2Share repository (https://eudat.eu/service-catalogue/b2share-0). Since 2006, Zöbelboden is part of the Long-term Ecosystem Research Network (LTER Austria) and serves as a research station for a number of universities and research institutes within Austria and beyond.

In the year 2024, besides running the standard ICP IM monitoring program at the site, we contributed to the scientific paper on heavy metal trends in the IM stations across Europe (Eklöf et al. 2024). The data gathered focusing on greenhouse gases was published in a data paper (Dirnböck et al. 2025). Trends in long-term changes of forest understory vegetation has been a focus of our work since many years. In 2024, we joined ReSurveyEurope a data initiative gathering long-term vegetation data (Knollová et al. 2024). In another initiative, forestREplot, besides publishing about declining nectar production in forests (De Schuyter et al. 2024), we successfully showed that nitrogen deposition was the main driver behind a surprisingly strong westward shift in forest plant species (Sanczuk et al. 2024).

In addition to the routine monitoring activities, in the year 2024 we focused on a forest inventory including a catchment-wide deadwood survey. Automated biodiversity monitoring continued in the framework of the global LifePlan project funded by the European Research Council (https://www2.helsinki.fi/en/projects/lifeplan) and will very likely continue in the course of the eLTER Research Infrastructure. Within a national biodiversity project, butterflies were recorded at the open-field site in the area.

Owing to its excellent instrumentation and long-term data, the Zöbelboden was included in numerous national, European, and international research projects (e.g. FWF DICE, ÖAW C-Alps, ACRP CCN-Adapt, ACRP CentForCSink, ACRP WoodNClimate, EU Live+ EnvEurope, EU SEE Orientgate, EU ExpeER, EU eLTER, EU Horizon2020 EcoPotential, EU Horizon Benchmark, EU Horizon FORWARDS, etc.). The manifold results were published in 75 scientific papers and a number of book contributions; they are continuously made available as TV, print and online media content. Currently, LTER Austria is pursuing an integration in the Europe-wide eLTER Research Infrastructure (https://elter-ri.eu/) in accordance with the Austrian strategy for research infrastructures. We recommend our short movie as an introduction to the site, its infrastructure, monitoring, and research activities (https://www.youtube.com/watch?v=cGKvIRGLHmw).

Acknowledgements

Long-term monitoring at Zöbelboden is funded through the Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (Now the Ministry of Agriculture and Forestry, Climate and Environmental Protection, Regions and Water Management). The Kalkalpen National Park and the Federal State Forests provide technical support.

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Report on National ICP IM activities in Estonia

Lõhmus, K.[1].

[1]*Estonian Environmental Research Centre (EKUK), Marja 4d, 10617 Tallinn, Estonia, e-mail: kairi.lohmus@klab.ee*

The Estonian integrated monitoring programme is run on two sites Vilsandi (EE01) and Saarejärve (EE02). The monitoring programme was started in 1994, that will be over 30 years in 2025. Currently both sites are managed by Estonian Environmental Research Centre (EKUK). The sites belong to Estonian national monitoring network.

Vilsandi is also a part of EMEP (the co-operative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe) network with its air and precipitation data (presented yearly). Data from Saarejärve is gathered under NEC Directive every six years (last presented in 2023) together with ICP Forests site (Tõravere) and ICP Waters site (Kiidjärve).

Currently the following programmes are conducted monthly with few exceptions: meteorology, air chemistry, precipitation chemistry, metal chemistry of mosses (in every 5 years), throughfall, stemflow, soil chemistry (in every 5 years), soil water chemistry, groundwater chemistry (in every 5 years only in EE02), runoff water chemistry (only in EE02), foliage chemistry, litterfall chemistry, vegetation (in every 5 years), trunk epiphytes (in every 5 years), microbial decomposition and toxicity assessment (in every 5 years only in EE02).

As in 2023, in 2024 only the normal yearly program was done, which includes meteorology, air chemistry, precipitation chemistry, throughfall, stemflow, soil water chemistry, runoff water chemistry, foliage and litterfall chemistry and microbial decomposition. Some smaller maintenance work was conducted, and no major changes occurred.

Report on National ICP IM activities in Spain

David Elustondo and Jesús Miguel Santamaría[1]

[1] *Laboratorio Integrado de Calidad Ambiental, LICA, Departamento de Química y Edafología, Universidad de Navarra*

The Spanish activities within the ICP Integrated Monitoring programme are coordinated by the BIOMA Institute for Biodiversity and the Environment of the University of Navarra, which also acts as the National Focal Point (NFP). BIOMA is responsible for the only ICP IM site currently active in Spain (ES02), located in the Natural Park of Señorío de Bertiz in northern Spain, and has been providing data to the programme since 2008.

The site is also integrated into the Spanish national monitoring network under the NEC Directive, contributing long-term datasets on key indicators of forest and ecosystem health.

Routine monitoring of all annual subprogrammes has been maintained in 2024, as in previous years. These include: AM (Meteorology), AC (Air chemistry), PC (Precipitation chemistry), TF (Throughfall), RW (Runoff water chemistry), LF (Litterfall chemistry), FC (Foliage chemistry), and SF (Stemflow). All sampling and data reporting were conducted in accordance with ICP IM protocols.

This year, new monitoring efforts have also been made, including the implementation of additional subprogrammes such as:

- BI (Tree bioelements and indicators): For the first time, this subprogramme was conducted to assess structural parameters and functional traits of trees. The goal is to assess the state and temporal changes in the chemical element content of tree biomass (including roots) and deadwood, which represent major nutrient pools in forest ecosystems. It also monitors trees as biological indicators of pollution and atmospheric changes and complements other subprogrammes (such as VS) related to nutrient cycling and vegetation structure.

- FD (Foliar Damage): During the summer months, foliar damage was assessed in 100 trees across the study catchment to evaluate the influence of biotic and abiotic factors on forest health.

- SW (Soil water chemistry): This subprogramme, which had been suspended since 2020 due to technical issues at the site, was resumed in 2024. It contributes to the long-term monitoring of groundwater, aiming to assess its relationship with atmospheric deposition and soil biogeochemical cycles.

In addition to the implementation of these new subprogrammes, significant efforts were made in data automation and standardization, leading to notable improvements in data processing workflows. These efforts aim to automate the entire workflow—from field sampling to the production of the final report—thereby enhancing data quality and ensuring full compatibility with international databases. Furthermore, this information will be used for the development of an open-access online viewer, expected to be launched in 2026, that will make all programme data freely available to users.

Moreover, a new meteorological station and a device for the continuous measurement of atmospheric pollutants (e.g., NO_2, O_3, $PM_{10}/PM_{2.5}$ and CH_4) were installed at the site to complement and improve environmental monitoring capabilities.

Finally, conversations were initiated with LTER Spain to explore the possible inclusion of the site within the Long-Term Ecological Research infrastructure, aiming to strengthen synergies and increase both national and international visibility.

Report on National ICP IM activities in Sweden

Lundin, L.[1], Rönnback, P.[1], Eveborn, D[2]., Grandin, U.[1], Jutterström, S.[3], Kronnäs, V.[3], Löfgren, S.[1], Kurén Weldon, J.[1], Moldan, F.[3], Simonsson, M.[1], Thunholm, B.[2], Whitlock, F.[2] and Östlund, M.[1]. 2025.

[1] Swedish University of Agricultural Sciences (SLU), Department of Aquatic Sciences and Assessment, Box 7050, SE–750 07 Uppsala, Sweden, e-mail: pernilla.ronnback@slu.se

[2] Geological Survey of Sweden (SGU), Box 670, SE–751 28 Uppsala, Sweden.

[3] Swedish Environmental Research Institute (IVL), Box 47086, SE–402 58 Gothenburg, Sweden.

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Introduction

The Swedish integrated monitoring programme is running on four sites distributed from south central Sweden (SE14 Aneboda), over the middle part (SE15 Kindla), to a northerly site (SE16 Gammtratten). The long-term monitoring site SE04 Gårdsjön F1 is complementary on the inland of the west coast and was influenced by long-term high deposition loads. The sites are well-defined catchments with mainly coniferous forest stands dominated by bilberry spruce forests on glacial till deposited above the highest coastline. Hence, there has been no water sorting of the soil material. Both climate and chemical deposition gradients coincide with the distribution of the sites from south to north (Table 1).

Table 1: Geographic location and long-term climate and hydrology at the Swedish IM sites (long-term average values, 1:1961–1990 and 2: 1991-2020).

	SE04	SE14	SE15	SE16
Site name	Gårdsjön F1	Aneboda	Kindla	Gammtratten
Latitude; Longitude	N 58° 03´; E 12° 01´	N 57° 05´; E 14° 32´	N 59° 45´; E 14° 54´	N 63° 51´; E 18° 06´
Altitude, m	114–140	210–240	312–415	410–545
Area, ha	3.7	18.9	20.4	45
Mean annual temperature (1), ºC Mean annual temperature (2), ºC	+6.7 +7.2	+5.8 +6.7	+4.2 +5.3	+1.2 +2.4
Mean annual precipitation (1), mm Mean annual precipitation (2), mm	1000 1080	750 730	900 900	750 660
Mean annual evapotransporation, mm	480	470	450	370

Mean annual runoff, mm (1)	520	280	450	380

The forest stands are mainly over 100 years old and at least three of them have about hundred years of natural continuity. Until the 1950's, the woodlands were lightly grazed in restricted areas. In early 2005, a heavy storm struck the IM site SE14 Aneboda. Compared with other forests in the region, however, this site managed rather well and roughly 20–30% of the trees in the area were storm-felled. In 1996, there were 317 logs contributing to the pool of large woody debris in the surveyed plots, which decreased to 257 in 2001. In 2006, after the storm, the number of logs increased to 433, corresponding to 2711 logs in the whole catchment. In later years, 2007–2010, bark beetle (*Ips typographus*) infestation has almost totally erased the old spruce trees. In 2011, more than 80% of the trees with a diameter at breast height over 35 cm where dead (Löfgren et al. 2014) and currently almost all spruce trees with diameter of ≥20 cm are dead. Also at SE04 Gårdsjön F1, considerable natural processes have influenced the forest stand conditions during later years, with increasing number of dead trees due to both storm felling and bark beetle infestation. Occasionally, access to the site is hampered due to fallen trees, creating a need for chain saw cleaning of footpaths. Also in SE15 Kindla, an increasing number of fallen trees and logs exert perturbation, forming gaps in the forest.

In the following, presented results mainly relate to 2023 and include climate, hydrology and water chemistry as well as some ongoing work at the four Swedish IM sites (Weldon, 2023).

Climate and Hydrology in 2023

Air temperature

Based on long-term (1961-1990) mean values from the Swedish Meteorological and Hydrological Institute (SMHI) and measured data from climate monitoring at the IM sites, the 2023 annual mean temperatures were 0.7-1.2 °C higher for all four sites. Largest deviation occurred at the northern site SE16 Gammtratten. A new, 30 years long climate period (1991-2020) now exists with higher temperature values than 1961-1990 showing somewhat lower temperature deviations in 2023 with 0.1-0.3 °C lower average temperature as noticed from the previous period (Table 1).

Compared with the on-site measured time series, 23 years at site SE16 Gammtratten and 27 years at the other sites, the temperatures in 2023 were higher at all sites with 0.6 °C at the two southern sites SE04 and SE14 but with 0.2-0.3 °C at the two northern sites SE15 and SE16. The mean annual temperature was above zero degrees for all four sites, but all sites had mean monthly temperatures below zero in December. At the two northern sites, also the winter period (November to March) showed degrees below zero.

Monthly average temperatures in the first month of the year were higher compared to long-term means of both reference periods (SMHI) at all stations. Larger deviations for the first period and smaller compared to the second period. October-December mainly showed lower temperature at all stations and especially compared to the second period. Higher temperatures were mainly observed for three stations with exception SE14 only having higher temperatures in June. The rest of the months showed variations between lower and higher temperatures compared to both reference periods.

Precipitation

Annual precipitations in 2023 were lower at sites SE14 Aneboda and SE16 Gammtratten. At the other two sites precipitations were higher. Low precipitations mainly occurred in spring and early summer but for SE16 Gammtratten most months showed lower precipitation when compared with reference periods. For the other three sites precipitations were mainly higher in January, July and August. In 2022 precipitation were lower at all four sites with larger deviations when compared with the second reference period.

Groundwater levels

High groundwater levels during winter and lower levels in summer and early autumn characterize the annual hydrological patterns of the southern catchments. At the northern locations, the general picture is low groundwater levels in winter when precipitation is stored as snow, raising levels at spring snowmelt followed by lower levels in summer due to evapotranspiration and groundwater outflow. However, depending on rainfall events in summer and/or autumn, the groundwater levels could occasionally be elevated also during these periods. Common are elevated levels in autumn. In 2023, levels at site SE14 Aneboda, in beginning of the year were comparably deep but were elevated already in January and stayed relatively high until April but receded then to low levels in July-August. Later, during autumn consecutively high levels were reached ending up close to ground surface at one location and on c. one metre depth at the other. Site SE15 Kindla showed the ordinary slightly more flashy patter and during most of the year on 0.2-0.5 m below ground surface. Only in May-June somewhat deeper levels occurred with at the most on one metre depth. In SE16 Gammtratten the levels followed the ordinary pattern with successively deeper levels to over three metres depth until snowmelt in May when levels rose to 1.5 m. After that mainly successively deeper levels occurred with a short exception for September when two meters depth after slightly heavy rainfall reached a small peak. Lower levels later were reached and the groundwater level ended up at close to three metres in the end of the year.

Discharge

Precipitation, evapotranspiration and groundwater levels affect the runoff patterns. The stream water discharge patterns (Fig. 1) also reflect the groundwater levels. Generally, snow accumulates during winter at the two northern IM sites, resulting in low groundwater levels and low stream water discharge. However, warm winter periods with temperatures above 0 °C have during a number of years contributed to snowmelt and excess runoff also during this season. However, only the most northern site SE16 Gammtratten had low flows throughout the 2023 first months. The other three sites showed similar patterns in beginning of the year with comparably high runoff in January and ordinary low flows in February with slightly high peaks in March but after that receding values until summer when runoffs were lower compared to average years (Fig. 1).

At SE04 Gårdsjön 2023, the pattern mainly agreed with the long-term mean apart from the high discharge in January and comparably high monthly values in July and August. Low runoff values occurred in May and June. In the end of the year values agreed with long-term average. Compared to the previous year 2022 runoff mainly were higher (Fig. 1).

The runoff at SE14 Aneboda in 2023 showed mainly similar pattern as for SE04 Gårdsjön with low values in summer. Autumn and end of the year were rather similar to the long-term mean. In the previous years 2022 and 2021 with lower runoff compared to long-term mean, while 2023 deviated when ordinary higher values occurred. (Fig. 1).

At site SE15 Kindla, the overall monthly runoffs throughout the year were similar to the long-term mean but with high monthly values in January, August and November. Lower values compared to the long-term mean were noticed for summer and in four months in end of the year, apart for November (Fig. 1)

At site SE16 Gammtratten, the monthly pattern resembled the long-term average. The snowmelt peak in May was higher and summer months June and July on comparably low values.

The snowmelt peak in some previous years started already earlier in April and in 2021 the snowmelt peak was early in March. In 2022 and 2023 the low summer runoff agreed with 2019 and 2020.

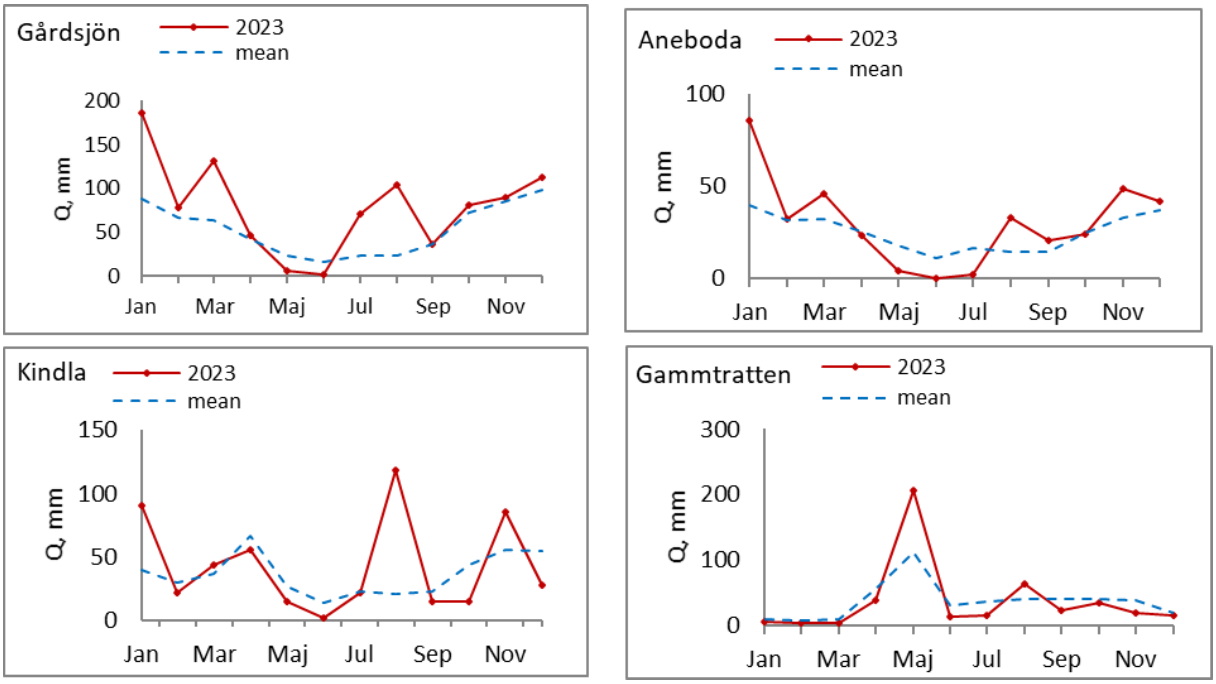

Figure 1: Monthly runoff patterns 2023 at the IM sites compared with the long-term monthly averages for the period 1996/97-2023. (Note the different scales at the Y-axis)

In 2023, the annual runoffs made up 42–73% of the annual precipitation (Table 2), which are almost normal 40–60%. SE04 and SE16 showed somewhat high rates with 73% and 68%, respectively. A high rate for the northern site could be expected and the relatively high precipitation on the West Coast would possibly contribute there. For SE14 Aneboda and SE15 Kindla 50% would be normal and agreed with 2023. SE14 Aneboda could be expected to have higher rate runoff due to the slightly poor forest cover due to bark beetle infestation. Throughfall was high for all sites resulting in low interception indicating lower canopy closure, being a result from forest damage at SE14 Aneboda and most likely decreasing forest stand covers at SE04 Gårdsjön and SE15 Kindla. For SE16 Gammtratten the stands are more open providing larger possibility for throughfall.

Slightly deviating values concerned somewhat high precipitation at SE04 Gårdsjön resulting in high runoff and somewhat low evapotranspiration. Together this indicate deteriorating forest stand. Also SE14 Aneboda had somewhat high precipitation but anyhow resulting in ordinary runoff and evapotranspiration. Possibly, runoff was slightly high but perhaps reflect the forest stand conditions.

Interceptions were similar at the sites, although could be expected lower at SE 14 Aneboda. SE15 Kindla showed reasonable values for its water balance. Also SE16 Gammtratten showed reasonable distribution for this northern site but anyhow low evapotranspiration.

Table 2: Compilation of the 2023 water balances for the four Swedish IM sites.

P – Precipitation, TF – Throughfall, I – Interception, R – Water runoff

	Gårdsjön SE04		Aneboda SE14		Kindla SE15		Gammtratten SE16	
	mm	% of P	mm	% of P	mm	% of P	mm	% of P
Bulk precipitation, P	1290	100	852	100	1036	100	654	100
Throughfall, TF	1014	79	639	75	674	65	536	82
Interception, P–TF	276	21	213	25	362	35	117	18
Runoff, R	944	73	363	43	514	50	446	68
P–R	346	27	489	57	522	50	207	32

Water chemistry in 2023

Low ion concentrations in bulk deposition (electrolytical conductivity 0.7–1.7 mS m^{-1}) characterised all four Swedish IM sites. The concentrations of ions in throughfall that include dry deposition, were higher at the two southern sites. At the central and northern sites SE15 Kindla and SE16 Gammtratten, the conductivity in throughfall (c. 0.8 mS m^{-1}) was almost the same as in bulk deposition indicating very low sea salt deposition and uptake of ions by the trees. At the two southern sites, sea salt deposition provides tangibly higher ion concentrations, especially at the west coast SE04 Gårdsjön site, 4 mS m^{-1} in throughfall and c. 2 mS m^{-1} in bulk deposition. The groundwater pathways are short and shallow in the catchments, providing rapid soil solution flow paths from infiltration to surface water runoff. However, the conductivity in soil water was higher compared to throughfall showing influences from evapotranspiration and soil chemical processes.

The deposition acidity has during the last 10 years been rather similar at all sites with somewhat higher pH values at three sites (0.1–0.4 units) in throughfall compared with bulk deposition. SE16 Gammtratten had similar pH (c. 5.2) in both bulk deposition and throughfall. The sites SE04 Gårdsjön and SE14 Aneboda had 0.2 and 0.4 pH units, respectively higher pH in throughfall compared with in bulk deposition (Table 3).

Table 3: Mean bulk deposition, pH throughfall and stream runoff values 2023 at the four Swedish IM sites. S and N in kg ha^{-1} yr^{-1}.

	SE04	SE14	SE15	SE16
pH, bulk deposition	5.1	5.1	5.4	5.2
pH, throughfall	5.3	5.5	5.5	5.2
pH, streamwater	4.5	4.5	4.7	5.7
S, bulk deposition	2.9	1.3	1.8	0.8
S, runoff	8,0	10.2	4.5	1,8
N, bulk deposition	6.0	3.5	7.9	1.7
N, runoff	4.1	2.2	1.2	0.9

The share of major anions in bulk deposition was similar for sulphate, chloride and nitrate at three of the sites, while chloride dominated at SE04 Gårdsjön due to the proximity to the sea. Sea salt showed clear influences on throughfall at SE04 Gårdsjön and at also SE14 Aneboda indicating effects of dry deposition. In throughfall, organic anions contributed significantly at all four sites. The chemical composition changed along the flow paths through the catchment soils and e.g. the sulphate concentrations were higher in stream water compared with deposition, indicating desorption or mineralization of previously accumulated sulphur in the soils. At SE16 Gammtratten and SE15 Kindla runoff of chloride and sulphate were on similar levels. At SE04 Gårdsjön chloride dominated while, sulphur showed a higher value at SE14 Aneboda.

Nitrogen runoff was lower compared to input by bulk deposition indicating storage of N in the catchments. Highest input was found in SE04 Gårdsjön and lowest in SE16 Gammtratten (Table 3). Share of retained N varied from 33-85% with low values in SE04 Gårdsjön and SE14 Aneboda, but the two other sites had values between 47 and 85%. SE15 Kindla was noticed with high NH_4-N input.

Organic-N was the dominating nitrogen fraction in all stream waters, ranging from 0.9 to 3.4 kg N_{org} ha^{-1}, yr^{-1} Inorganic N runoff were low (≤0.13 kg N_{inorg} ha^{-1}, yr^{-1}) at three sites. SE 04 Gårdsjön showed higher values with 0.7 kg N_{inorg} ha^{-1}, yr^{-1}. The higher inorganic flow at SE04 Gårdsjön depended partly on high N-deposition. SE14 Aneboda had somewhat higher inorganic N output with 0.13 kg N_{inorg} ha^{-1}, yr^{-1} and were likely result from deteriorated forest stands. SE15 Kindla and SE16 Gammtratten showed low flows.

In summary, the four Swedish IM sites show low ion concentrations and permanently acidic conditions in the aqueous media. In stream water, only the northern site SE16 Gammtratten had buffering capacity related to bicarbonate alkalinity. Organic matter has an impact on the water quality with respect to colour, metal complexation, and nutrient concentrations at all sites, but less at SE15 Kindla, where rapid soil water flow paths provide relatively low DOC concentrations but acidic waters. At SE14 Aneboda, the forest dieback provides a relatively high share of runoff as well as high nitrate concentrations compared with the other three sites. However, mainly there were low concentrations of inorganic nutrients ammonia, nitrate and phosphate. At SE04 Gårdsjön, deposition is strongly influenced by input from the sea.

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