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Convention on Long-range Transboundary Air Pollution

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

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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 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. The emphasis of the report is in the work done during the programme year 2021/2022 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
- National Reports on ICP IM activities are presented as annexes.

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

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Preface

Welcome to the 31st Annual Report, and also the first produced by the new Programme Centre at the Swedish University of Agricultural Sciences. As many of you will be aware by now, the Programme Centre and database have moved to SLU after many years in the care of SYKE in Finland, where the previous team did a fantastic job. We would like to take the opportunity to thank them for all their work, wish those retiring a happy retirement and say that we look forward to further co-operation with the others!

The new 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 co-chairs of IM, Ulf Grandin and Salar Valinia are of course also in Sweden, facilitating close co-operation with the Programme Centre.

As part of the move there is a new website for IM which you can find at www.slu.se/en/icp-im and a new PDF version of the monitoring manual which can be downloaded from the link above. There are no changes in methodology in this new version, but changes in format, layout, improved illustrations and some new introductory text.

As the handover period has involved a great deal of administrative and practical work for both the previous and new teams, this edition of the Annual Report is lighter than usual on scientific content. We hope to be back to normal by the next edition however!

James Kurén Weldon, on behalf of the Programme Centre

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 a number of 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, http://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. 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) 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 and TIN were also analysed. Large spatial variability in the input and output fluxes of SO_4 and TIN reflects important gradients of air pollution effects in Europe, with the highest deposition and runoff water fluxes in southern Scandinavia, 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 deposition and bulk deposition of TIN was found at 90% and 65% of the sites, respectively. Output fluxes of non-marine SO_4 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 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 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 was explained by variations in runoff and SO_4 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 may lead to a slower recovery of surface waters than those predicted by the decrease in SO_4 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 the 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 xSO4, and consequently acidity in precipitation, have substantially decreased in IM areas. Inorganic N (TIN) deposition has decreased in most of the IM areas, but to a lesser extent than that of xSO4. Substantially decreased xSO4 deposition has resulted in decreased concentrations and output fluxes of xSO4 in runoff and decreasing trends of TIN concentrations in runoff – particularly for NO3 – 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 xSO4 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-squares 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. Work on this issue is continuing.

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 hydrogen ions 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 SO4, NO3 and NH4 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, and the results were consistent with previous observations from European forested ecosystems. Decreasing SO4 and base cation trends in runoff waters were commonly observed at the ICP IM sites. At some sites in the Nordic countries decreasing NO3 and H+ trends (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 Scandinavia.

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 SO4 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 NO3 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.

The recent 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 SO4 and TIN were evaluated for the period 1990–2012 (Vuorenmaa et al. 2017). These results clearly showed the regional-scale decreasing trends of SO4 in deposition and runoff/soil water, and suggested that IM catchments have increasingly responded to the decreases in S emissions and depositions of SO4 since the early 1990s. Decreased nitrogen emissions also resulted in decrease of inorganic N deposition, but to a lesser extent than that of SO4, 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 SO4 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 SO4 results in generally higher leaching fluxes of SO4 than those of inorganic N in European forested ecosystems. SO4 thus remains the dominant source of actual soil acidification despite the generally lower input of SO4 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 nitrogen 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). Previous work was published by Dirnböck et al. (2014). This study utilised a new ICP IM database for biological data and focussed on effects on forest floor vegetation from elevated nitrogen deposition..

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.

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) utilised long-term monitoring data from 28 Integrated Monitoring sites to analyse temporal trends in plant species cover and diversity. At sites where nitrogen 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 nitrogen 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 nitrogen 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 sulphur and nitrogen 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_2 in air, NH_4^+, NO_3^- and SO_4^{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, 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.

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 to a large extent 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 will be used for establishment of background heavy metal concentrations in forested compartments and risk assessments of heavy metals.

The results presented by Eklöf et al. (2020) showed that declining metal deposition and/or recovery from acidification have resulted in decreasing Cd and Pb concentrations in runoff at many of the European ICP IM sites during the last 30 years. In contrast, the Hg concentrations in runoff did only show one statistically ($p<0.05$) significant decreasing trend. Catchment Cd, Pb and Hg input-output budgets were also calculated for the four ICP IM sites in Sweden. At catchment level, the mass-balances for Cd and Pb showed that the exports via runoff (RW) could account for only 13–70% and 21–56%, respectively, of the total inputs (TF+LF). These results are in agreement with other studies, indicating metal accumulation in the soils.

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 uppermost forest soil mor-layer in spite of 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. Aluminium (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. Fast additions 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 sulphate, total inorganic nitrogen (TIN) and acidity in deposition substantially decreased at the sites. Decreases in sulphur (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 nitrogen (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 H^+ 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 total inorganic nitrogen (TIN) in runoff. At the majority 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 nitrogen.

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).
- Participation in the development of the European LTER network (Long Term Ecosystem Research Network, www.lter-europe.net) and eLTER RI (European Research Infrastructure) 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)
- Cooperation with other external organisations and programmes, particularly the 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 2021 to June 2022

Meetings

- Salar Valinia represented ICP IM at three virtual meetings with the European Commission about the NEC Directive, 24 June 2021, 28 October 2021, and 27 January 2022.
- Martin Forsius, Salar Valinia, and Ulf Grandin represented ICP IM at the Seventh Joint Session of the Working Group on Effects and the Steering Body to EMEP, held on-line 13–16 September 2021.
- Martin Forsius, Martyn Futter, Ulf Grandin, and James Kurén Weldon took part in the virtual eLTER PPP and PLUS project meeting 20-22 October 2021.
- James Kurén Weldon represented ICP IM and gave a presentation about current activities at the ICP Vegetation Task Force meeting, held on-line 21–24 Feb 2022.
- Ulf Grandin, Salar Valinia and James Kurén Weldon represented ICP IM at the videoconference of the Joint meeting of EMEP Steering Body and Working Group on Effects Extended Bureau, 21–24 March 2022.
- James Kurén Weldon represented ICP IM and gave an online presentation about current activities, at the CDM meeting, held in Sitges, Spain 6-8 April 2022.
- Thomas Dirnböck represented ICP IM and gave a presentation about current activities, at the ICP Modelling and Mapping Task Force meeting, held on-line 3-5 May 2022.
- The thirtieth meeting of the Programme Task Force on ICP Integrated Monitoring was held at Miraflores de la Sierra (and online), Spain 10–12 May 2022.
- Martyn Futter, Ulf Grandin, and James Kurén Weldon took part in the eLTER PPP and PLUS project meeting, held in Mallorca, Spain 16–20 May 2022.
- James Kurén Weldon represented ICP IM and gave a presentation about current activities, at the ICP Forests Task Force meeting, held on-line 2–3 June 2022.

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

- A scientific paper 'Nitrogen deposition causes eutrophication in bryophyte communities in central and northern European forests' (Weldon et al. 2022) was published. This paper was prepared in co-operation with ICP Forests.
- A scientific paper on Hg and HM trends in concentrations and fluxes across ICP Integrated Monitoring sites in Europe (Eklöf et al.) is planned for 2022.
- A scientific paper on impacts of internal catchment-related nitrogen parameters to total inorganic nutrient nitrogen (TIN) leaching (Vuorenmaa et al.) will be finalised in 2022.
- The Programme Centre and Task Force Chairs contributed to the WGE report on the revision of the Gothenburg protocol.
- Task Force Chairs together with the Programme Centre and a group of experts from the IM community developed the Extended IM concept.

Activities and tasks planned for 2022–2023

Activities/tasks related to the programme's present objectives, carried out in close collaboration with other ICPs/ Task Forces

Carried over from the previous workplan, ICP IM will produce the following papers:

- Scientific paper on Hg and HM trends in concentrations and fluxes across ICP Integrated Monitoring sites in Europe (WGE item 1.1.1.1.6), report published in AR29, peer reviewed scientific publication in preparation.
- Scientific paper on the impacts of catchment characteristics, climate, and hydrology on N processes (WGE item 1.1.1.15, listed as: Scientific paper on impacts of internal catchment related nitrogen parameters to total inorganic nutrient nitrogen (TIN) leaching), report published in AR29, peer reviewed scientific publication in preparation.

ICP IM activities on the WGE 2022–23 work plan:

- 2022: Operationalise and advertise Extended IM as an attractive monitoring protocol, aiming at adding more ecosystem types in the ICP IM monitoring.
- 2023: Scientific paper on modelling and assessment of biodiversity and ecosystem impacts, in co-operation with e.g., Centre for Dynamic Modelling (CDM).

Other activities

- Contribution to the revision process of the Gothenburg Protocol, in a coordinated process of the WGE.
- Maintenance and development of central ICP IM database at Swedish Agricultural University (SLU).
- Arrangement of the 31st Task Force meeting (2023).
- Preparation of the 32nd ICP IM Annual Report (2023).
- Preparation of the ICP IM contribution to assessment reports of the WGE
- Participation in meetings of the WGE and other ICPs

Activities/tasks aimed at further development of the programme

- Participation in the development of the European LTER network (Long Term Ecosystem Research Network, www.lter-europe.net) and eLTER-RI (European Research Infrastructure) 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).
- Participation in the activities of other external organisations, particularly the International Long Term Ecological Research Network (ILTER, www.ilter.network).

Published reports and articles 2021–2022

Evaluations of international ICP IM data and related publications

Forsius, M., Posch, M., Holmberg, M., Vuorenmaa, J., Kleemola, S., Augustaitis, A., Beudert, B., Bochenek, W., Clarke, N., de Wit, H., Dirnböck, T., Frey, J., Grandin, U., Hakola, H., Kobler, J., Krám, P., Lindroos, A-J., Löfgren, S., Pecka, T., Rönnback, P., Skotak, K., Szpikowski, J., Ukonmaanaho, L., Valinia, S., Váňa, M. 2021. Assessing critical load exceedances and ecosystem impacts of anthropogenic nitrogen and sulphur deposition at unmanaged forested catchments in Europe. Science of the Total Environment 753.

Kleemola, S. & Forsius, M. (eds.), 2021. 30th Annual Report 2020. Convention on Long-range Transboundary Air Pollution, ICP Integrated Monitoring. Reports of the Finnish Environment Institute 37/2021, Helsinki. 64 p. http://hdl.handle.net/10138/333713

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

Akhmetova B.R., Aleksandrova M.S. Comparison of the results of measuring the levels of sulfates in the atmospheric air using filters of various types // School-Conference of Young Scientists "Prokhorov Weeks". October 19-21, Moscow. - 2021 - p.135-136.

Andronikov, A.V., Novák, M., Krám, P., Šebek, O., Andronikova, I.E., Štěpánová, M., Vítková, H., Antalová, E., Komárek, A. 2021. δ53Cr values of catchment runoff exhibit seasonality regardless of bedrock Cr concentrations: role of periodically changing chromium export fluxes. Hydrological Processes 35(12): 1-12, e14434.

Burtseva L.V., Pastukhov B.V., Konkova, E. S. Assessment of lead, cadmium, copper, and mercury concentration in water of lower Volga-river, EGU General Assembly Conference Abstracts, EGU21-11767? 2021 https://doi.org/10.5194/egusphere-egu21-11767

Hood-Nowotny, R., Schmittner, K., Ziss, E., Leitner, S., Watzinger, A., Gorfer, M. et al. 2021. Functional response of an Austrian forest soil to N addition. Environ. Res. Commun. 3 (2), 025001. DOI: 10.1088/2515-7620/abe8c7.

Ivanov V.A., Pozdnyakova E.A., Gromov S.A. Mann-Kendall test for assessing trends in the intake of pollutants from stationary sources on the territory of the Russian Federation / Applied Physics and Mathematics. - 2021. - No. 3. - p. 32-39/

Kruchina E.B., Burtseva L.V., Pozdnyakova E.A. Organization and technology of environmental pollution background monitoring. Environmental Control Systems - 2021 / Abstracts of the International Scientific and Practical Conference. - Sevastopol, November 9-12, 2021 - Sevastopol: IK IPTS, 2021. – p. 28.

Kruchina E.B., Kozlova E.N. Critical loads: application for assessing the state of ecosystems on the territory of the Russian Federation // Innovative technologies for protecting the environment in the modern world: materials of the All-Russian Scientific Conference with International Participation (Kazan, March 18–19, 2021) / Ministry of Education and Science of Russia; Kazan. nat. research technol. un-t. - Kazan: Publishing House of KNRTU, 2021.-p. 1447-1451

Oulehle, F., Chuman, T., Evans, C., Goodale, C., Hruška, J., Krám, P., Navrátil, T., Tesař, M., Ač, A., Urban, O., Tahovská, K. 2021. Dissolved and gaseous nitrogen losses in temperature forests controlled by soil nutrient stoichiometry. Environmental Research Letters 16, 064025: 1–11.

Oulehle, F., Fischer, M., Hruška, J., Chuman, T., Krám, P., Navrátil, T., Tesař, M., Trnka, M. 2021. The GEOMON network of Czech catchments provides long-term insights into altered forest biogeochemistry: From acid deposition to climate change. Hydrological Processes 35: e14204, 1–18.

Pisek, J., Erb, A., Korhonen, L., Biermann, T., Carrara, A., Cremonese, E., Cuntz, M., Fares, S., Gerosa, G., Grünwald, T., Hase, N., Heliasz, M., Ibrom, A., Knohl, A., Kobler, J., Kruijt, B., Lange, H., Leppänen, L., Limousin, J.-M., Serrano, F. R. L., Loustau, D., Lukeš, P., Lundin, L., Marzuoli, R., Mölder, M., Montagnani, L., Neirynck, J., Peichl, M., Rebmann, C., Rubio, E., Santos-Reis, M., Schaaf, C., Schmidt, M., Simioni, G., Soudani, K. & Vincke, C. 2021. Retrieval and validation of forest background reflectivity from daily Moderate Resolution Imaging Spectroradiometer (MODIS) bidirectional reflectance distribution function (BRDF) data across European forests, Biogeosciences, 18(2):621–635. DOI: 10.5194/bg-18-621-2021

Weldon, J. & Grandin, U. 2021. Weak recovery of epiphytic lichen communities in Sweden over 20 years of rapid air pollution decline. The Lichenologist 53(2): 203–213. DOI: 10.1017/S0024282921000037

Zheng, W., Lamačová, A., Yu, X., Krám, P., Hruška, J., Zahradníček, P., Štěpánek, P., Farda, A. 2021. Assess hydrological responses to a warming climate at the Lysina Critical Zone Observatory in Central Europe. Hydrological Processes 35(9): 1-17, e14281.

Monitoring sites and data

The following countries have continued data submission to the ICP IM database during the period 2016–2021: 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 2015–2021 is 48 from fifteen countries. Sites from Canada, Latvia and United Kingdom only contain older data.

An overview of the data reported internationally to the ICP IM database is given in Table 1.1. Additional earlier reported data are available from sites outside those presented in Table 1.1. and Fig. 1.1. Locations of the ICP IM monitoring sites are shown in Fig. 1.1.

Figure 1: Location and status of ICP IM sites.

Table 1.1. 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	95-20	95-20	93-20		93-20	99-04	04	93-20		95-20	-	92-20	93-20				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	89-20	89-20	89-20	89	89-20		02-20	07-20	08-20	89-20	-			07	-									
CZ02 LYSINA	67-20	93-96	90-20		91-20		93	90-20	89-20	89-20	91-20	94	08	07	11		15	94			14-15		10	
DE01 FORELLENBACH	90-20	90-20	90-20	90	90-20	90-05	90-11	90-20	88-20	90-20	-	90-20	90-20		-	90-14	90-08		00	92-95		94-20	91-02	90-95
DE02 NEUGLOBSOW	67-20	98-20	98-20		98-20	04-20	04-16	98-20	98-20		98-20	06-20	04-20				04-17							
EE01 VILSANDI	95-20	94-20	94-20	94-20	94-20	94-20	94-20	94-20	95-96	-	-	94-20	94-20	-	-	94-17	94-97			94-04		94-20		94
EE02 SAAREJÄRVE	94-20	98-20	94-20	94-16	94-20	94-20	94-20	95-20	95-14	94-20	96	94-20	94-20			96-17	96-12	12		94-15	94-17	96-20	98-14	
ES02 BERTIZ	08-17	08-19	07-19		07-19	08-19	10-15	07-18		07-19		08-18	08-19			07-12	07		07					
FI01 VALKEA-KOTINEN	88-20	94-20	88-20	88-96	89-17	89-99	88-89	89-17		88-20	87-20	88-17	90-16		90-93	88-91	88-09			88-97		90	87-89	87
FI03 HIETAJÄRVI	88-20	93-00	88-20	89-96	89-17	89-99	88	89-17		88-20	87-20	88-17	90-16		90	88-91	90-09			90-97		90-91	87-89	
FI06 PALLASJÄRVI	13-19		14-20		16-17			02-17		04-20	04-20	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	93-20	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	97-20	97-19		97-19	97-19	95	02-08		-	-	97-19		-	-	97-19	09		99-09					
IT06 PIANO LIMINA	99-19	97-16	97-20		97-20	97-20	95	19-20		-	-	97-19		-	-	97-19	09		99-09					
IT07 CARREGA	97-21	97-20	97-20		97-20	97-00	95	19-20		98-13	-	97-19		-	-	97-19	09		99-09					
IT09 MONTE RUFENO	97-21	97-20	97-20		97-20	97-00	95	02-08		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					
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	94-20	93-20	93-20		06-19	99-20	12-20		00-20	93-20	20	02-20	93-20	93-20			93
LT03 ZEMAITIJA	90-13	95-19	95-19	06-20	95-19		94-20	95-20	95-20	95-20		06-19	99-20	95-20		00-20	94-20	20	02-20	94-20	94-20			94
NO01 BIRKENES	87-20	87-20	87-20	92	89-20		87-11	86-20	87-88	87-20	-	86-17	87-02		-	91-18	86-18			86				
NO02 KÅRVATN	87-91	87-20	87-20	88	89-11		89-13	89-10		87-20	-	89-09	89-02		-	92-10	89-09							
NO03 LANGTJERN		87-97	77-20		86-03		91-13	91-03		87-20		86-03	87-02											
PL01 PUSZCZA BORECKA	06-20	16-20	16-20		16-20		17	10-20			16-20		06-20				16							
PL05 WIGRY	06-20	16-20	16-20		16-20		19	06-20		16-20			05-20				16							
PL06 PARSENTA	10-20	16-20	94-20		96-20			10-20		94-20			10-20											
PL07 POJEZIERZE CHELMINSKI	16-20	16-20	16-20				18	20		16-20														
PL08 KAMPINOS	09-20	16-20	16-20		16-20		16	12-19		16-20			10-20				16							
PL09 LYSOGORY	05-20	16-20	16-20		16-20			05-20		16-20			05-20				16							
PL10 BESKIDY	94-20	16-20	94-20		02-20			11-20		94-20			09-20				16							
PL11 WOLIN	16-20	16-20	16-20		17-20			16-20		16-20			16-20											
PL12 ROZTOCZE	16-20	16-20	16-20		16-20			16-20		16-20			16-20				16							
RU03 CAUCASUS BR	89-94	89-20	89-98																					
RU04 OKA-TERRACE BR	89-06	89-20	89-98	90										93-99		93-20	93-02			93		94-96		
RU12 ASTRAKHAN BR	93-94	93-20	93-94																					
RU13 CENTRAL FOREST BR	93	93-94	93													09-20	18-20							
RU14 VORONEZH BR	94	94-20	94-98																					
RU16 VELIKIY ISLAND				89-90			89	89	89						93-99	93-19	91-94			89-94	93	94-95		91
RU47 KURSK																18-20								
SE04 GÅRDSJÖN F1	87-20	88-20	87-20	95	87-20		95-10	87-20	79-20	87-20	-	99-19	96-19		-	97-01	95-19	91-20	91-20	96-16	92-20	95-19		
SE14 ANEBODA	96-20	96-20	96-20	95	96-20		96-11	95-20	96-20	96-20	-	99-19	95-19		-	97-01	82-19	96-16	06-16	97-17	97-20	95-19		
SE15 KINDLA	97-20	96-20	96-20		96-20		97-12	95-20	97-20	96-20	-	97-19	95-19		-	98-01	96-20	98-18	98-18	98-18	97-20	95-19		
SE16 GAMMTRATTEN	99-20	99-20	99-20		99-20		00-18	00-20	00-20	99-20		99-19	00-19			00-01	99-19	99-19	99-19	00-20	00-20	00-19		

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Annex I

Report on National ICP IM activities in Austria

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The only ICP Integrated Monitoring station in Austria, Zöbelboden, is located in the northern part of the National Park Kalkalpen at 550 to 956 m.a.s.l. As measurements according to the ICP IM Programme started in the year 1992, we are celebrating 30 years of successful monitoring this year. 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 Programme, the data and metadata is publicly available at the DEIMS-SDR portal (https://deims.org/8eda49e9-1f4e-4f3e-b58e-e0bb25dc32a6). Since 2006, Zöbelboden is part of Long-term Ecological Research (LTER Austria) and serves as a research station for a number of universities and research institutes within Austria and beyond. This development led to additional instrumentation such as a CO_2 flux tower and soil chamber measurements, sapflow and automated dendrometers, and a high-resolution runoff probe for NO_3, DOC, and TOC (https://www.lter-austria.at/en/cwn-project/). Last year, automated biodiversity monitoring started in the framework of the global LifePlan project (https://www2.helsinki.fi/en/projects/lifeplan). Currently, LTER Austria is pursuing an integration in the Europe-wide eLTER Research Infrastructure in accordance with the Austrian strategy for research infrastructures. Owing to its excellent instrumentation and long-term data, the Zöbelboden was and is included in numerous national, European, and international research projects (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, ACRP EXAFOR, EU Horizon2020 eLTER PLUS, etc.). The manifold results were published in totally 53 scientific papers and a number of book contributions; they are continuously made available as TV, print and online media contributions.

Acknowledgements

Long-term monitoring at Zöbelboden is funded through the Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology. The National Park Kalkalpen and the Federal State Forests provided technical support and co-funding.

Annex II

Report on National ICP IM activities in the Czech Republic – CZ01 Anenské catchment

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Introduction

Monitoring of small forest catchments in the frame of the International Cooperation Programme – Integrated Monitoring within the Czech Republic is carried out at two locations: Anenské catchment CZ01 (49°34´24´´ N, 15°4´49´´ E, 487–543 m a. s. l.) and Lysina CZ02 (50° 03´N, 12° 40´E, 829–949 m a. s. l.). The Anenské catchment is located in the central part of the Czech Republic and belongs to Košetice Observatory's activities. Detailed evaluation of Lysina catchment is not included in this report, more information can be found in Oulehle et al 2021.

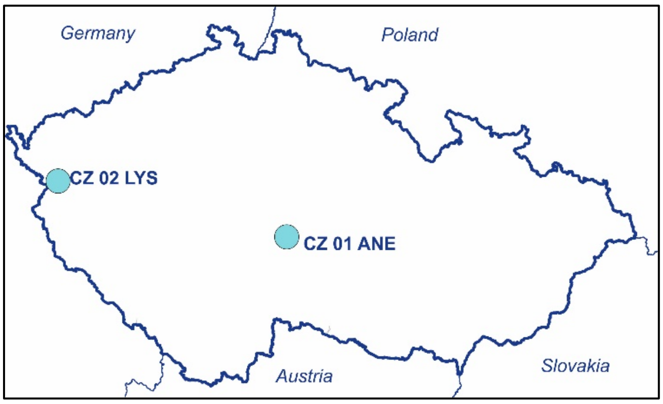

Figure 1: ICP IM small forest catchments in the Czech Republic - Anenské catchment (ANE) CZ01, Lysina catchment (LYS) CZ02.

Site description - Anenské catchment

The monitored catchment of 250 meters long stream was until 2021 approximately 90% forested; the rest of the area was composed of agricultural land. The forested part was mainly covered by spruce monocultures, with stands of about 90 years of age with an admixture of pine, beech, larch, and birch. The bark beetle calamity in the Czech Republic, which started in 2019, forced the forest owners to log infested trees. Some parts of the catchment area have been logged; the planting of new trees is being done simultaneously.

Table 1. Basic characteristics of Anenské catchment.

	Catchment area km^2	average (1990–2020) annual flow $l.s^{-1}$	average specific runoff $l.s.^{-1}.km^{-2}$
Anenské catchment	0.285	0.430	1.490

A hydrological spillway, equipped with an ultrasonic probe with a recording unit for continuous measurement of the water level, flow and air temperature, is at the mouth of the forest stream. At regular monthly intervals, surface water samples are taken and analysed.

The soils in the Anenské catchment (also called the Forest Stream) are developed on biotitic paragneiss. These are acid brown forest soils of the distric cambisol type. Soil sampling and chemical analyses were carried out almost regularly each 5 years, the last one was performed in 2020. Close to two soil probes, the soil lysimeters were installed to monitor soil water chemistry. Sampling is conducted at two depth levels, 20 and 40 cm below the surface. Samples are collected monthly.

The input of substances from the atmosphere to other components of the natural environment is measured as atmospheric deposition both in the open area (bulk precipitation) of the Košetice Observatory and under the spruce canopy (throughfall).

Climate and Hydrology

The Aneské catchment is located in the middle warm climatological area MT5 (according to Quitt classification). The average temperature was 8.2 °C (long-term temperature normal period 1991–2020), 9.1 °C in 2020. The warmest month in 2020 was august (18.6 °C), the coldest month was January (0.7 °C) (Fig. 2). The year 2020 was the fifth warmest year in the history of measurement at Košetice Observatory. The average sum of precipitation at the open area (total precipitation) was 658.1 mm (long-term precipitation period 1991–2020), the year 2020 was above precipitation long-term mean (799.0 mm). Precipitation under the canopy (throughfall –THF) reach an average of 60% of total precipitation (THF = 397.7 mm, normal precipitation period 1991–2020), in 2020 was the sum of THF precipitation 590.7 mm.

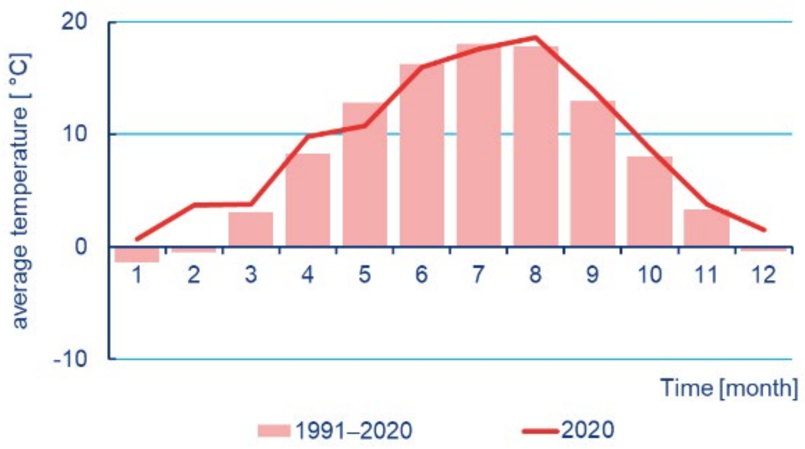

Figure 2: Monthly variability of air temperature at Košetice Observatory 1991–2020.

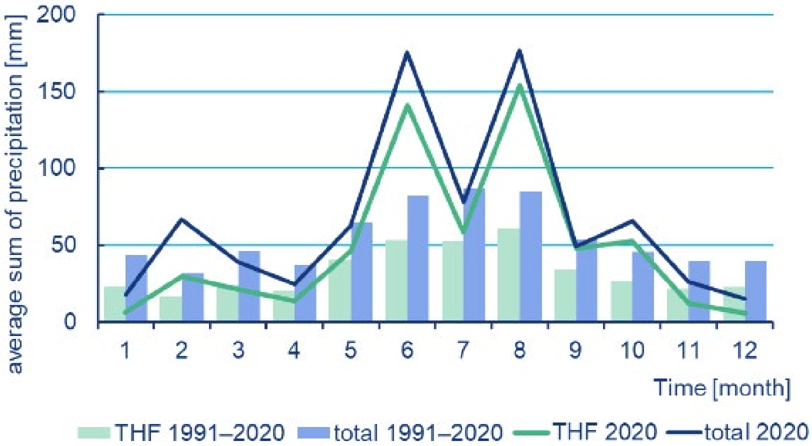

Figure 3: Monthly variability of precipitation amount at the open area (total) and under the canopy (THF), Košetice Observatory, Anenské catchment, 1991–2020.

The average runoff reached 0.4 $l \cdot s^{-1}$ (1991–2020), in 2020 was average value 0.5 $l \cdot s^{-1}$. Some changes are visible in monthly variability when comparing long-term period to result from 2020. The highest runoff was typically recorded in March and April. However, the runoff reached its maxima in August in 2020 (Fig. 4).

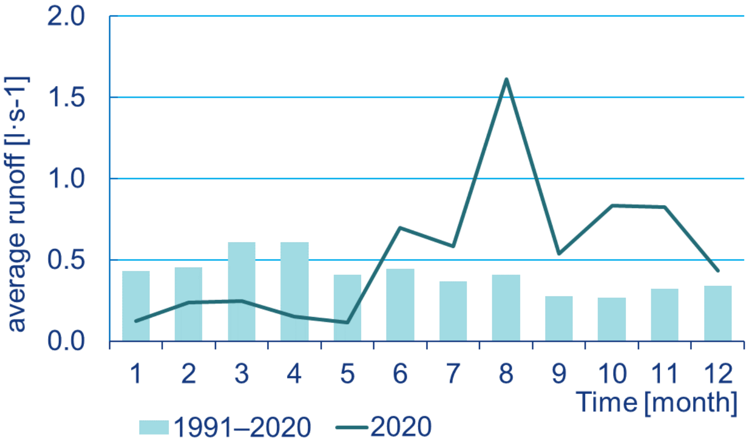

Figure 4: Monthly variability of average runoff of Forest stream at Anenské catchment

Water chemistry

The quality of water is regularly recorded in precipitation (THF, Bulk, Wet-only) and in stream water as well at ANE from 1990. Although the list of analysed substances at ANE is broad, we focus on pH, NO_3_N, NH_4_N, SO_4_S, Cd, Ni, and Pb concentration in this contribution. Each substance is evaluated during the period of measurement (predominantly average of 1990–2020) and in 2020. Values of pH reflected the changes in acidification from the beginning of measurement in 1990. Precipitation median pH was 5.0–5.2, increasing to 5.9 in 2020. Only a small pH decrease is observed in stream water, where median pH was 7.1 and 6.9 in 2020. The concentration of NO_3_N was the highest in THF; the maximum concentration 10.4 $mg \cdot l^{-1}$ was measured in April 2003. Median NO_3_N concentrations during the whole period varied from 0.5 to 1.9 $mg \cdot l^{-1}$ in precipitation, in stream water was 0.9 $mg \cdot l^{-1}$ In 2020 the median NO_3_N concentrations decreased to range 0.2–0.8 mg·l^{-1} in precipitation, the median NO_3_N concentration in stream water was 0.9 mg·l^{-1}.

The maximum concentration NH_4_N 14.441 mg·l^{-1} was measured in THF in June 1990. Median NH_4_N concentrations during the whole period corresponding to 0.543 to 1.941 mg·l^{-1} in precipitation, in stream water was median NH_4_N concentration 0.008 mg·l^{-1} (same in 2020). In 2020 the median NH_4_N concentrations decreased to 0.465–1.009 mg·l^{-1} in precipitation.

Very high inputs of SO_4_S from the atmosphere during the last decades of the 20th century (except the last 10 years) was pronounced by high outputs of SO_4_S in stream water. Median SO_4_S concentrations during the whole period ranged from 0.4 to 2.8 mg·l^{-1} in precipitation, in stream water median SO_4_S concentration was 14.3 mg·l^{-1}. In 2020 the median SO_4_S concentrations decreased to 0.2–0,7 mg·l^{-1} in precipitation. On the contrary, the median SO_4_S concentrations reached 24.6 mg·l^{-1} in stream water.

Concentrations of Cd and Pb were higher in THF, and Bulk precipitation compared to Wet-only during the whole period. Median Cd concentrations were ranging from 0.03 to 0.11 µg·l^{-1} in precipitation, in stream water median Cd concentration was 0.04 µg·l^{-1}. In 2020 the median Cd concentrations decreased to 0.02–0.03 µg·l^{-1} in precipitation, in stream water the median Cd concentrations was 0.02 µg·l^{-1}.

Median Ni concentrations varied from 0.4 to 1.2 µg·l^{-1} in precipitation, in stream water median Ni concentration was 3.6 µg·l^{-1} in 1990–2020. Three episodes with very high concentrations in bulk precipitation were recorded in 2020 (namely in January 19.9 µg·l^{-1}, November 14.8 µg·l^{-1} and December 20.0 µg·l^{-1}), Ni concentrations in THF and Wet-only precipitation were 0.3 and 0.9 µg·l^{-1} respectively. Ni median concentrations in stream water was 3.7 µg·l^{-1}.

Median Pb concentrations were ranging from 2.5 to 0.7 µg·l^{-1} in precipitation, in stream water median Pb concentration was 0.6 µg·l^{-1} in 1990–2020. The median Pb concentrations decreased to 0.2–0.6 µg·l^{-1} in precipitation, in stream water the median Pb concentrations dropped to 0.2 µg·l^{-1} in 2020 (Fig. 5).

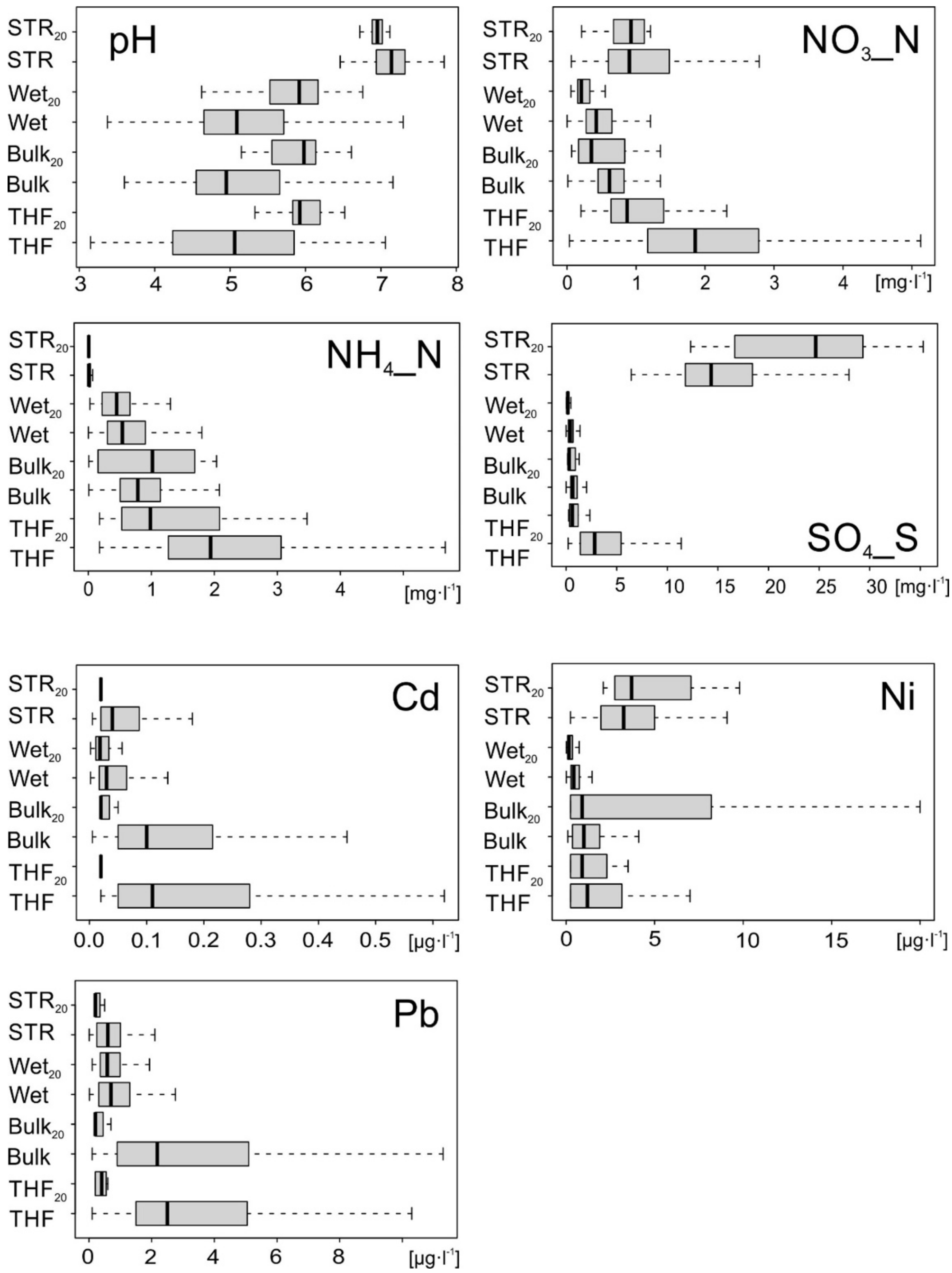

Figure 5: Boxplot of pH values and concentrations of NO3_N, NH4_N, SO4_S, Cd, Ni, and Pb in precipitation (THF – throughfall, Bulk, Wet – Wet-only) and stream water (STR – stream water), in period 1990–2020 and in 2020.

Annex III

Report on National ICP IM activities in Estonia

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Introduction

The Estonian integrated monitoring programme is run on two sites (EE01 Vilsandi and EE02 Saarejärve). The monitoring programme was started 1994, that is over 25 years. In Vilsandi the site has been managed by Estonian Environmental Research Centre since the beginning. In Saarejärve the site was managed by IM Saare from 1994 to 2015, in 2016 Estonian Environmental Research Centre took over.

Starting from 2019, the programme's intensity was changed. Site monitoring ended at the spruce area in Saarejärve, some subprogrammes were stopped all together. 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).

In 2016 the stream's weir's location was changed slightly in Saarejärve to get more accurate results. In October 2021 the precipitation collector was moved to a more suitable place in Saarejärve. The old spot was overgrown with shrub and trees.

Major trends over the past ten years (2012-2021)

All the trends have been calculated with weighed yearly averages which takes into account the amount of precipitation as well. In 2021 there was 557 mm of precipitation at Saarejärve (EE02) and 709 mm at Vilsandi (EE01). The long run average precipitation amount in Estonia is 662 mm. Since Vilsandi is on a small island at the west coast of Saaremaa (Estonia's biggest island), it is strongly affected by the Baltic Sea. Saarejärve on the other hand is inland.

Precipitation Chemistry (PC)

The concentrations of NO3-N (from 0.18 mgN/l in 2012 to 0.16 mgN/l in 2021) and SO4-S (from 0.31 mgS/l in 2012 to 0.20 mgS/l in 2021) have decreased over the past 10 years in precipitation at Saarejärve (EE02). At the same time the trends show an increase in dissolved organic carbon from 3.2 mg/l in 2012 to 3.6 mg/l in 2021, in 2020 the DOC concentration in precipitation was even as high as 7.1 mg/l. The reasoning could be also due to the old location of the collector. Next few years in the new location should show the true concentrations of DOC and if it is actually increasing or decreasing instead.

In Vilsandi (EE02) the trends show a decrease in the concentrations of NH4-N (from 0.31 mgN/l in 2012 to 0.16 mgN/l in 2021), SO4-S (from 0.32 mgS/l in 2012 to 0.21 mgS/l in 2021), Ca2+ (from 0.67 mg/l in 2012 to 0.26 mg/l in 2021) and Cd (from 0.093 µg/l in 2012 to 0.019 µg/l in 2021), however there has been an increase in the pH from 4.9 in 2012 to pH 5.2 in 2021.

Fig. 1 shows the change in the concentrations of nitrates in precipitation at EE02. According to Mann-Kendall analysis the significance level of this change was the highest for Saarejärve. Another significant change is shown on fig. 2 that depicts the trends with cadmium concentrations at EE01.

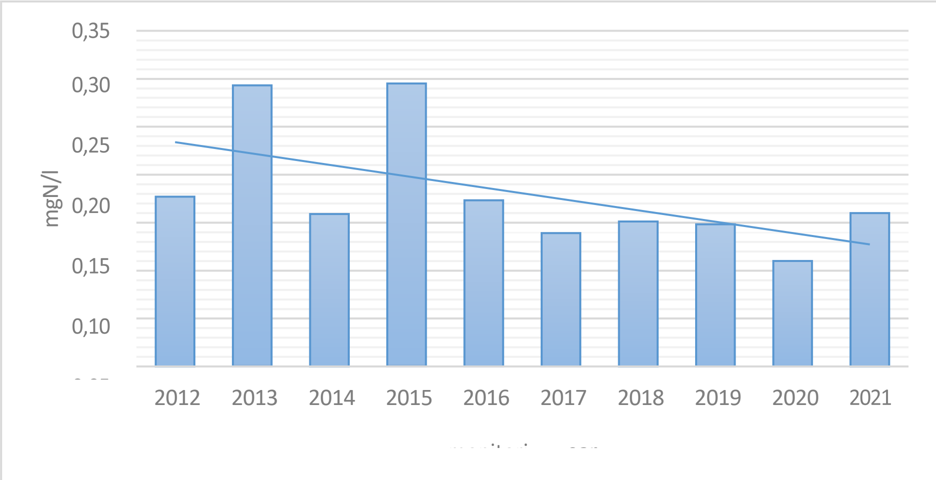

Figure 1. The change in the concentrations of NO3-N (mgN/l) in precipitation at Saarejärve (EE02) from 2012 to 2021.

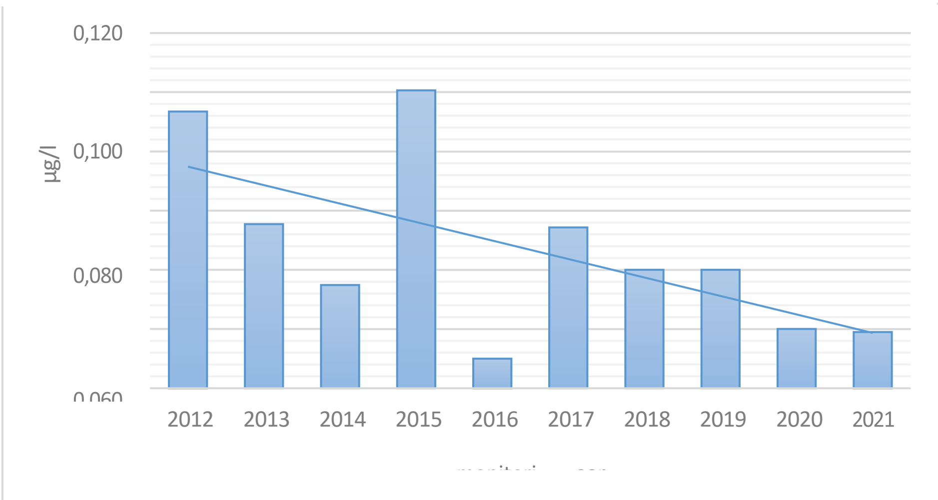

Figure 2. The change in the concentrations of Cd (µg/l) in precipitation at Vilsandi (EE01) from 2012 to 2021.

Throughfall (TF)

Over the past 10 years there has not been any major changes in throughfall, however there have been few smaller trends. Like in precipitation, the concentration of nitrates has decreased in both Saarejärve (EE02) and Vilsandi (EE01) throughfall. At Saarejärve monitoring area there has also been smaller decreases in the concentrations of sulphates (0.32 mgS/l in 2012 to 0.20 mgS/l in 2021), magnesium (from 0.33 mg/l to 0.22 mg/l) and total nitrogen (from 1.2 mg/l to 0.73 mg/l). As for Vilsandi there has been an increase in pH levels (pH 4.6 in 2012 to pH 5.0 in 2021) and decreases in the concentrations of calcium (from 2.9 mg/l to 1.1 mg/l), copper (from 5.8 µg/l to 2.1 µg/l), nickel (from 5.0 µg/l to 0.53 µg/l) and dissolved organic carbon (from 23 mg/l to 16 mg/l).

Stemflow (SF)

The trends in stemflow at Saarejärve (EE02) show significant increase with total phosphorus concentrations from 0.030 mg/l in 2012 up to 0.067 mg/l in 2021. In 2019 the total phosphorus was at its highest concentration of 0.19 mg/l. The changes of this trend are shown on fig. 3.

Other trends were not as significant, however there has been a decrease in sulphates (from 0.81 mgS/l to 0.44 mgS/l), sodium (from 1.7 mg/l to 1.2 mg/l) and dissolved organic carbon (from 101 mg/l to 52 mg/l) concentrations and increase in pH levels from pH 3.9 to pH 4.3 at EE02.

According to Mann-Kendall trend analysis concentrations in stemflow at Vilsandi (EE01) show decrease in sulphates from 2.0 mgS/l to 1.0 mgS/l over the past 10 years (2012-2021). There has also been a decrease in metal concentrations – copper (from 12 µg/l to 4.3 µg/l), nickel (from 15 µg/l to 1.0 µg/l) and zinc (from 287 µg/l to 53 µg/l).

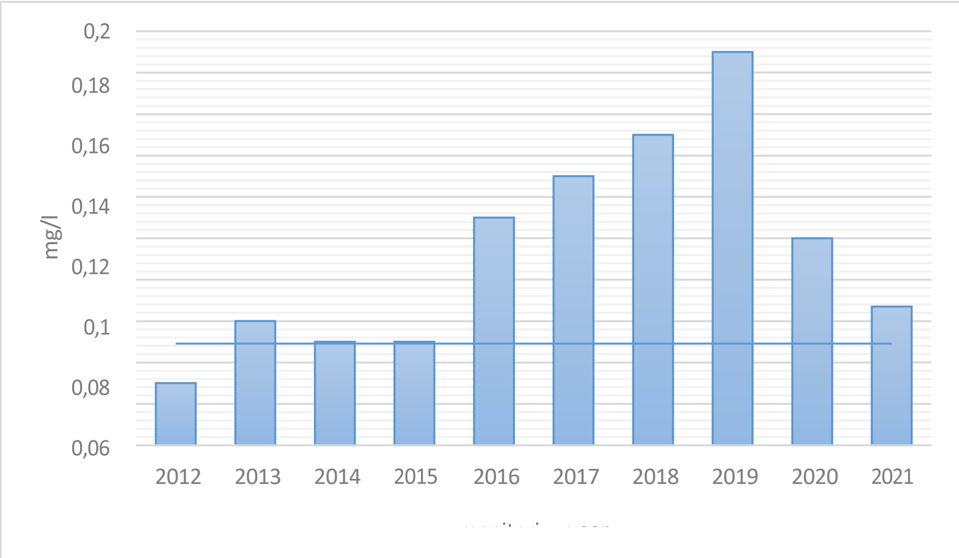

Figure 3. The change in concentrations of total phosphorus (mg/l) at Saarejärve (EE02) stemflow from 2012 to 2021.

Soil water chemistry (SF)

There have been few major trends in the soil water at both sites – Saarejärve (EE02) and Vilsandi (EE01). In the first depth level (10 cm) at EE02 the trends show decrease in cadmium and labile aluminum concentrations. In the second depth level (40 cm) at EE02 the soil water contains decreasing amounts of NO3-N but increasing amounts of total nitrogen. The changes are shown in fig. 4.

At EE01 in the first depth level at 17 cm there has been a decrease in lead concentrations and an increase in dissolved organic carbon levels. In the second depth level at 35 cm there has been a decrease in copper concentrations and an increase in sodium levels. These trends are depicted in fig. 5.

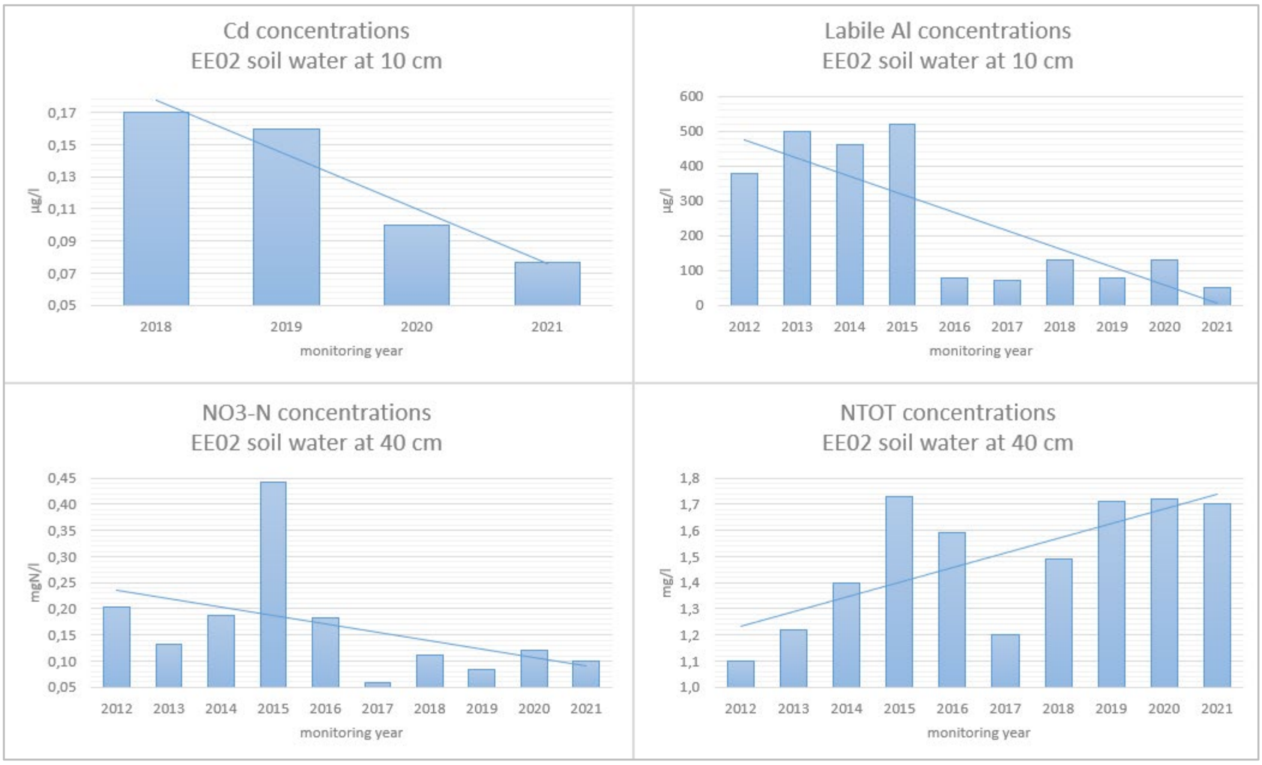

Figure 4. Major trends in the soil water at Saarejärve (EE02) from 2012 to 2021.

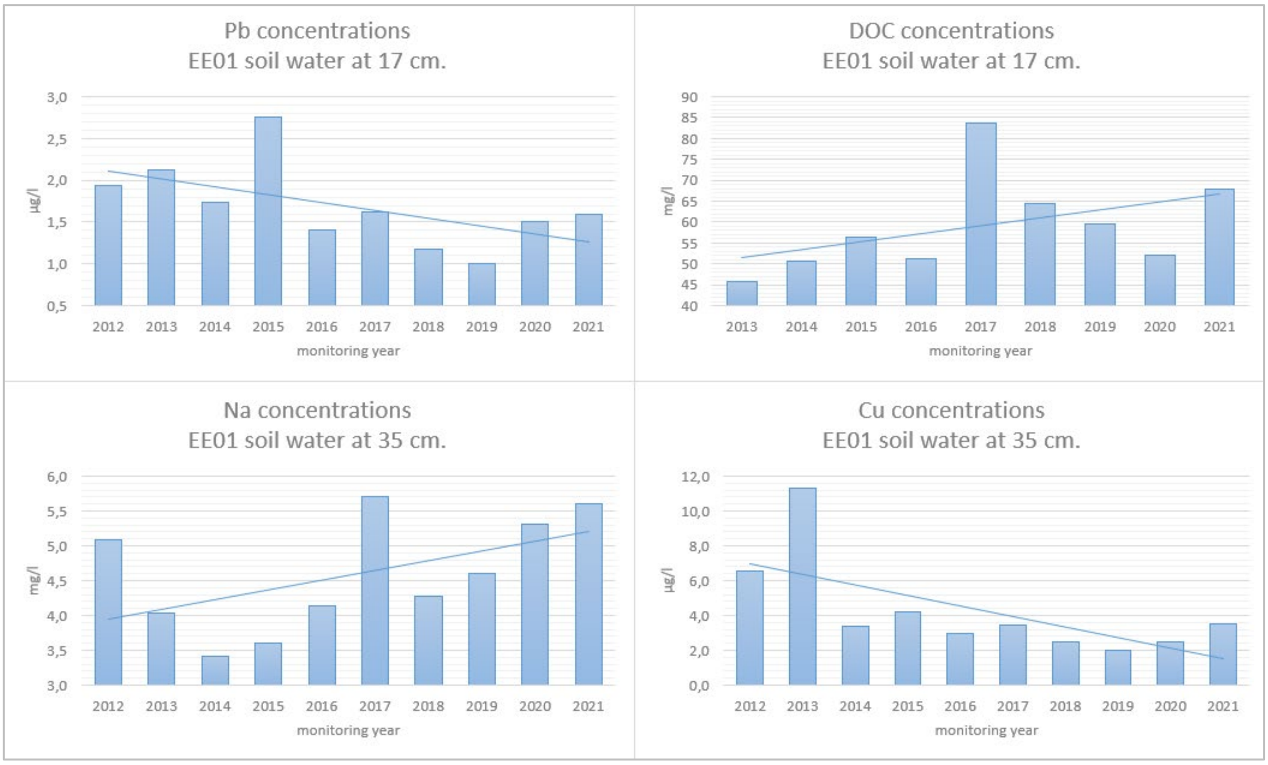

Figure 5. Major trends in soil water at Vilsandi (EE01) from 2012 to 2021

Runoff water chemistry (RW)

Samples for runoff chemistry are gathered only in Saarejärve (EE02) once a month. There have not been any major changes from 2016 to 2021. Earlier years have not been concluded in analysis due to the change in weir's location and recalculations of the flow. The following table shows some of the yearly average concentrations together with the flow.

Table 1. Yearly weighed average concentrations in Saarejärve (EE02) runoff from 2016 to 2021.

	pH	NH4-N (µgN/l)	NO3-N (µgN/l)	Cl (mg/l)	SO4-S (mgS/l)	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)	NTOT (µg/l)	PTOT (µg/l)	ALK (mmol/l)	DOC (mg/l)	COND (mS/m)	FLOW (l/(s*km^2))
2016	7.3	25	1365	4.3	2.9	54	10	3.6	1.3	2068	27	3.0	20	32	1.5
2017	7.8	46	1258	4.2	1.8	66	12	3.7	1.1	1931	37	3.9	18	37	1.4
2018	7.6	90	1339	3.8	3.1	56	11	3.4	0.86	1837	27	3.1	11	32	1.0
2019	7.5	25	1141	4.3	7.4	45	9.0	4.0	0.81	1883	25	2.3	16	28	0.87
2020	7.6	19	816	3.3	3.0	48	9.6	3.9	0.66	2003	50	2.8	24	30	0.91
2021	7.5	17	1310	4.2	3.0	51	9.9	3.9	0.91	1806	29	2.9	16	38	1.0

Conclusions

The concentrations of SO4-S and NO3-N show a steady decrease at both of the monitoring sites in Estonia. Usually, the waters contain higher concentrations of elements during the first half of the year and as well during dry periods at which the samples are more concentrated due to lower amount of precipitation.

There has also been a decrease in heavy metals concentrations at both sites, which suggest that the accumulated amounts in lichen and soil will decline over the years.

Annex IV

Report on National ICP IM activities in Ireland

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Ireland remains in contact with ICP Integrated Monitoring, and that contact has helped to make a case nationally for monitoring. No monitoring activity has been carried out since 2017. Under the NEC Directive, a new National Ecosystems Monitoring Network, operated by Ireland's Environmental Protection Agency, is being developed. Ireland's IM Site Brackloon, a semi-natural ancient oakwood plot on Podzol soil, is prioritised as a Level 2 site within NEMN for progressive installation of deposition monitoring, and ammonia passive sampling initially.

Annex V

Report on National ICP IM activities in Russia

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In 2021, as part of the ICP IM implementation, atmospheric air sampling was carried out at RU04, RU03, RU12 and RU14 sites. The sulfur and nitrogen dioxide content, as well as the aerosol sulfates content, was determined in the samples.

In 2021, the participation of the IGCE analytical laboratory in international comparative tests was carried out. Samples of the 63rd WMO intercalibration were received. The intercalibration results analysis showed that the relative errors in the determination of sulfates vary from -24 to 9%, and for nitrates, from -3 to 19%. These errors are within the range of satisfactory measurements. The average error in the determination of sulfur and nitrogen compounds does not exceed 15%.

In the course of field work in 2021 at RU04, a description of the permanent observation sites necessary for the further implementation of bioindication subprograms was completed.

Within the framework of the FD and VG subprograms, annual measurements and observations were carried out at the stations of the MSP KM RU04, RU13, RU16, RU47.

Figure 1: Fieldwork at an IM site

Annex VI

Report on National ICP IM activities in Spain

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An overview of the subprogrammes carried out in the ES02 plot in Spain.

Last year we had an incident as a consequence of a storm that practically destroyed the TF plot, causing us to lose the AC and TF sub-programme data for a couple of months and the SW and SF sub-programmes so far. Due to the characteristics of the forest on our site, storm-related incidents are common. However, we have never had one so destructive. As a consequence of the incident, we have been forced to prepare an alternative plot and to buy new equipment to replace the old one. Our intention is to install the new plot during the next few months thus recovering the SW and SF subprogrammes.

The rest of subprogrammes (AC, AM, PC, TF, FC, RW, LF) continued as foreseen. In addition, this year we repeated the 5-year subprogrammes VG and SC.

Finally, we are negotiating an agreement with the Clean Air Unit of the Ministry for Ecological Transition to obtain funds that will allow us to continue the monitoring and undertake improvements on the site. The agreement follows the site's accession to the Spanish NEC Directive monitoring network and is important because it could help us to stabilize and renew our field instruments (something very necessary in our site right now).

As for the Extended ICP IM, we explained it to the Ministry and the reception was good. They are interested in the NEC network, and it is not unreasonable to think that these plots will transfer their data to the IM programme, as the harmonized procedures of the ICPs will be used. The aim of the NEC team is to continue working in the network during the next months. This year is impossible because of the lack of funding, but the idea is to look for potential plots (not forests) currently in use for research or monitoring purposes and then, discuss how to finance them. We are currently assessing 3-4 possibilities to be discussed before 2023.

Annex VII

Report on National ICP IM activities in Sweden

Lundin, Lars [1], Löfgren, Stefan[1], Rönnback, Pernilla[1], Bovin, Kajsa[2], Eveborn, David [2], Grandin, Ulf[1], Jutterström, Sara[3], Kurén Weldon, James[1], Pihl Karlsson, Gunilla[3], Moldan, Filip[3] & Thunholm, Bo[2]

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[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.*

The programme is funded by the Swedish Environmental Protection Agency.

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 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, 1961–1990).

	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, °C	+6.7	+5.8	+4.2	+1.2
Mean annual precipitation, mm	1000	750	900	750
Mean annual evapotranspiration, mm	480	470	450	370
Mean annual runoff, mm	520	280	450	380

The forest stands are mainly over 100 years old and at least three of them have about a 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, the total number of large woody debris in the form of logs was 317 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 were 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 2020 and include climate, hydrology, and water chemistry as well as some ongoing work at the four Swedish IM sites (Löfgren, 2021).

Climate and Hydrology in 2020

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 2020 annual mean temperatures were 0.6-1.0 ^{o}C higher than normal at all four sites. Largest deviation occurred at the southern site SE14 Aneboda. A new climate reference period (1991-2020) now exists with higher temperatures than 1961-1990 leading to somewhat lower temperature deviations compared with the previous period. Compared with the on-site measured time series, 20 years at site SE16 Gammtratten and 24 years at the other sites, the temperatures in 2020 were higher at all four sites with 1.2 - 1.7 ^{o}C. SE16 Gammtratten had the lowest temperature difference while SE04 Gårdsjön and SE14 Aneboda had the highest. The annual mean values were the highest at all four stations as compared with the measurement periods. The variations between years are considerable, especially for the last nine years, with over 3°C at three of the sites. Smaller variations, only 2.4°C, were found at the central site SE15 Kindla. Low temperatures were observed in the years 2010 and 2012 with 2–3 ^{o}C below the 24 years average at three sites, while SE15 Kindla only deviated with 1 ^{o}C below the series mean. In the year 2020 and for all sites, higher temperatures were observed in January and February together with November and December. Similar conditions were noticed the two previous years 2018 and 2019. However, only the northern site SE16 Gammtratten showed temperatures below 0°C throughout the winter months.

Compared with the SMHI long-term average values (1961–1990), the precipitation amounts in 2020 were higher at the three sites SE04 Gårdsjön, SE14 Aneboda and SE16 Gammtratten with 300 mm at the two first mentioned sites and ca 100 mm at the northern site. In 2019, the two southern sites showed larger precipitation amounts as well, while the northern SE16 Gammtratten showed lower values. At SE15 Kindla, the precipitation amounts were close to the long-term mean both in 2020 and 2019. This deviates from 2018 when all sites had lower amounts compared to the long-term mean. In 2020, the precipitation distribution between months showed low values for the spring months April and May, while larger amounts were recorded in the beginning and the end of the year. At SE14 Aneboda and SE15 Kindla this pattern was less obvious in the end of the year with relatively low precipitation amounts in November.

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. In 2020, only the site SE16 Gammtratten started the year on low levels while all other sites had fairly high groundwater levels. At SE14 Aneboda, snowmelt and rain elevated the groundwater levels somewhat in February-March. At SE15 Kindla, the groundwater levels remained high in winter and spring. At SE16 Gammtratten, the snowmelt peak occurred in May-June where after evapotranspiration and groundwater discharge lowered the levels until September. Autumn rains turned the groundwater levels higher at SE14 Aneboda and SE16 Gammtratten. At the later site, snow storage hampered the groundwater recharge in November and December. At SE15 Kindla, the groundwater level was close to ground surface in the beginning and at the end of the year. At SE14 Aneboda and SE15 Kindla, summer rains elevated the groundwater levels in June and July. At the SE15 Kindla site, fairly low groundwater levels occurred in August with 1.2 m below the ground surface being lower than the previous year but not as low as in 2018 with 1.5 m. The groundwater levels in 2020 were relatively similar to those observed in 2016-2017 and 2019.

The stream water discharge patterns reflect the groundwater levels (Fig. 1).

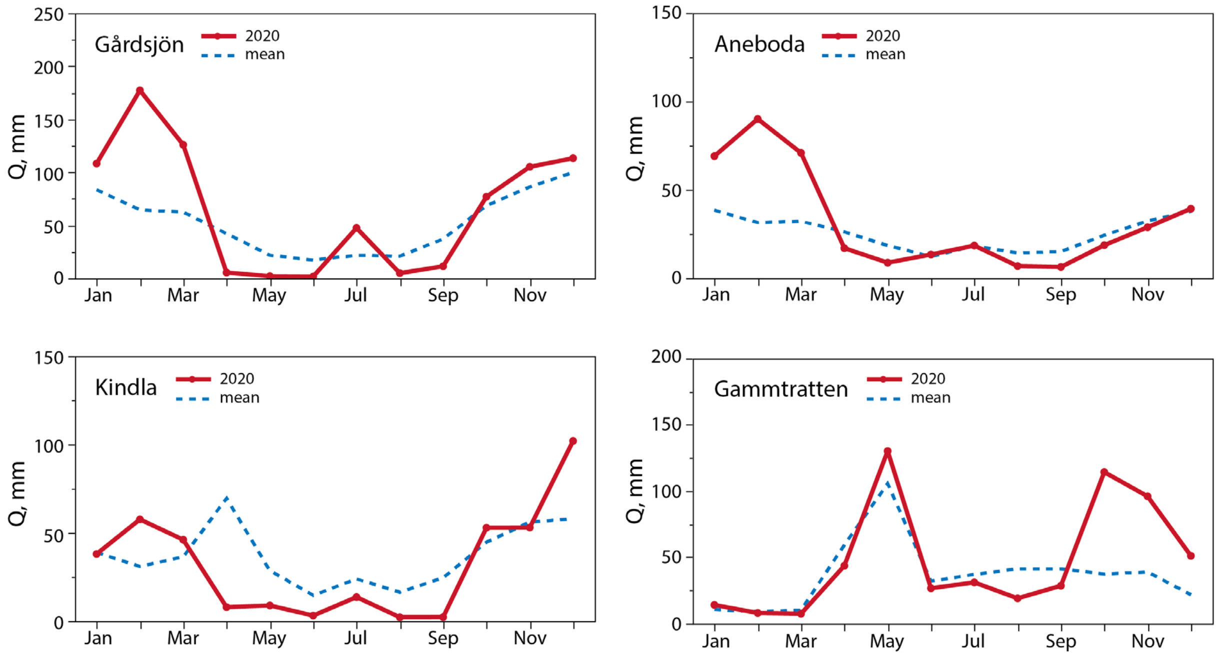

Figure 1. Monthly discharges at the four Swedish IM sites in 2020 compared with the monthly averages for the period 1996–2020 (mean). Note the different scales at the Y-axis.

Precipitation, evapotranspiration, and groundwater levels affect the runoff patterns. At SE16 Gammtratten, this pattern was fairly typical with a snowmelt peak in April and May and lower discharges in summer and autumn but with a peak in October-November before low temperatures caused snowfall and snow accumulation with lower discharges. The snowmelt peak agreed with the long-term runoff pattern, deviating somewhat from 2019 when it occurred slightly earlier. At SE04 Gårdsjön, the runoff pattern mainly agreed with the long-term mean apart from the high discharges in February-March. A similar pattern also occurred in 2019. In the summer of 2020, the discharge was low with a small peak in July. Autumn discharge resembled the long-term mean. At SE15 Kindla, the snowmelt peak was early and occurred in February-March. Similarly, to 2019, the summer runoff was comparably low. Autumn rains increased the discharge from October to December, reaching higher levels than usual at the end of the year. In 2020, the runoff at SE14 Aneboda was higher than usual in January-March. From April to December, the runoff pattern was fairly similar to the long-term average (Fig. 1).

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 2020 winter period. At SE15 Kindla, runoff was low in January, but similarly to the runoff patterns at the two southern sites exhibiting high runoff in the beginning of the year (Fig. 1), the discharge increased already in February.

In 2020, the annual runoff made up 47–67% of the annual precipitation (Table 2), which is close to the normal range 40–60%. The highest share (67%) occurred at SE16 Gammtratten, reflecting the colder climate in the north. At SE04 Gårdsjön, it is quite normal that runoff constitutes almost 2/3 of the precipitation, though being slightly lower in 2020 (59%) due to the large amounts of precipitation. At SE14 Aneboda, storm felling, followed by bark beetle infestation, have reduced the forest canopy cover and thereby the interception. For 2020, however, the total evapotranspiration was estimated to 390 mm, which agrees with the common ration 50/50 E to R and is within the range of previous years. The site SE15 Kindla showed the lowest runoff share with 47%, reasonably close to the 50/50 E to R range. SE15 Kindla had the highest interception even though the stand canopy is slowly declining. In 2016 and 2018, the annual runoff range was wider than usual and made up 31–83% of the annual precipitation at the four sites.

Table 2. Compilation of the 2020 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	1322	100	777	100	822	100	846	100
Throughfall, TF	1038	79	670	86	528	64	652	77
Interception, P–TF	284	21	107	14	294	36	194	23
Runoff, R	780	59	387	50	387	47	571	67
P–R	542	41	390	50	435	53	275	33

At the northern site SE16 Gammtratten, throughfall and bulk precipitation use to be fairly similar, but in 2020 throughfall only reached 77%. The latter is probably a more reasonable estimate compared with earlier years. Presumably, snow deposition infers large uncertainties, which in earlier years could have caused erroneous estimates of especially bulk precipitation. Related to the 2020 precipitation, however, both evapotranspiration and runoff gave reasonable amounts. In summary and based on the estimated evapotranspiration (P-R), the years 2020 and 2019 showed reasonable evapotranspiration being lowest at the northern SE16 Gammtratten site (Table 2). In 2018, the very dry summer furnished low evapotranspiration at all four sites.

Water chemistry in 2020

Low ion concentrations in bulk deposition (electrolytical conductivity 1–2 mS m^{-1}) characterised all four Swedish IM sites. The concentrations of ions in throughfall, which includes dry deposition, were higher at the three more southern sites. At the northern site SE16 Gammtratten, the conductivity in throughfall (0.7 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 most southern sites, sea salt deposition provides tangibly higher ion concentrations, especially at the west coast SE04 Gårdsjön site with 4.8 mS m^{-1} in throughfall and 2.0 mS m^{-1} in bulk deposition.

The groundwater pathways are fairly 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 (0–0.3 units) in throughfall compared with bulk deposition. In 2020, however, SE04 Gårdsjön, SE15 Kindla and SE16 Gammtratten had similar pH (5.1-5.3) in both bulk deposition and throughfall. The site SE14 Aneboda had 0.6 pH units higher pH in throughfall compared with in bulk deposition (Table 3).

Table 3. Mean deposition chemistry values 2020 at the four Swedish IM sites. S and N in kg ha^{-1} yr^{-1}.

	SE04	SE14	SE15	SE16
pH, bulk deposition	5.1	5.0	5.3	5.1
pH, throughfall	5.3	5.6	5.3	5.2
S, bulk deposition	3.7	1.8	1.6	1.1
N, bulk deposition	6.6	5.1	4.5	2.4

During the soil solution passage through the catchment soils, organic acids were added and leached on its way to stream runoff. In the upslope recharge areas, pH in soil water in the upper soil layers (E-horizon) was mainly lower than in throughfall with ≤ 0.8 pH-units for the three southern sites. SE16 Gammtratten had the lowest pH-value in soil water with 4.4, being 0.8 units lower compared with throughfall. However, in the organic rich discharge areas at SE15 Kindla and SE16 Gammtratten, pH was higher in soil solution compared with throughfall while the opposite occurred at SE14 Aneboda and SE04 Gårdsjön.

In the recharge areas, the buffering capacity (ANC) in soil water and groundwater varied between negative and positive values, but most frequently it was on the negative side, especially at SE14 Aneboda with -0.09 mEq L^{-1}. This may be an effect of nitrification. In the discharge areas of this site, the buffering capacity in groundwater was considerable with 0,07 mEq L^{-1}. At SE15 Kindla, the groundwater ANC was high with 0.21 mEq L^{-1}, while SE04 Gårdsjön and SE16 Gammtratten showed lower values with -0.02 and 0.04 mEq L^{-1}, respectively, being lower also compared with SE14 Aneboda. Bicarbonate (HCO_3^-) occurred at SE15 Kindla, SE16 Gammtratten and SE14 Aneboda with 0.23, 0.04 and 0.04 mEq L^{-1}, respectively, but possibly not at SE04 Gårdsjön. The latter is not measured but indicated by the very low pH of 4.4 and high DOC concentration (15 mg L^{-1}).

The stream waters were acidic with pH values below 4.8 at all sites except SE16 Gammtratten having an annual average pH of 5.6. The stream water buffer capacity was positive at all sites (ANC $\geq$ 0.012 mEq L^{-1}), except at SE04 Gårdsjön with a negative ANC (-0.019 mEq L^{-1}). However, also SE15 Kindla had acidic stream water with ANC close to zero. Anions of weak organic acids and bicarbonate alkalinity contributed to the positive ANC (0.1 mEq L^{-1}) at SE16 Gammtratten. At SE15 Kindla and SE04 Gårdsjön, the stream waters were more acidic compared with the other two sites probably due to oxidation of organically bound sulphur related to natural sources and the legacy from earlier sulphur deposition. In SE04 Gårdsjön deposition of sea salt contributed to the acidic conditions.

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 also at 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 in deposition, indicating desorption or mineralization of previously accumulated sulphur in the soils. In the recharge area of SE14 Aneboda, nitrification have contributed to relatively high nitrate concentrations in the soil water. However, the nitrate concentrations turned lower in 2019 and 2020.

At the northern site SE16 Gammtratten, the sulphate concentrations in soil water and stream water were considerably higher compared to throughfall, indicating release from the soil pool. Organic anions and HCO_3^- dominated the stream water anion flow (2/3 of the anions) to be compared with 1/3 at SE15 Kindla and SE14 Aneboda and 1/8 at SE04 Gårdsjön.

The cation and anion relations reflect different soil and soil water processes. In deposition, Na^+ dominated the base cations for all sites. This was valid also in stream water except for at the northern site SE16 Gammtratten where Ca^{2+} showed the highest concentrations. At sites SE04 Gårdsjön and SE14 Aneboda, Cl^- concentrations were higher compared Na^+ while Na^+ dominated at the other two sites. A higher leakage of Na^+ compared to Cl^- in to the stream water indicate weathering of minerals and release of base cations. At SE04 Gårdsjön, Mg^{2+} showed the second highest base cation concentrations in runoff water, also reflecting the marine influence, while Mg^{2+} and Ca^{2+} were quite equal at the other three sites.

Besides effects on ANC and pH, the stream water chemistry was to a considerable extent influenced by organic matter. At SE14 Aneboda, the DOC concentration was high with 29 mg L^{-1} while SE04 Gårdsjön showed 15 mg DOC L^{-1}. The other two sites had lower DOC concentrations with 10 and 12 mg L^{-1} at SE15 Kindla and SE16 Gammtratten, respectively. High DOC concentrations create prerequisites for metal complexation and transport as well as high fluxes of organic nitrogen. This was the dominating nitrogen fraction in all stream waters, ranging from 0.21 to 0.66 mg N_{org} L^{-1}. Inorganic N concentrations were low ($\leq$0.042 mg N_{inorg} L^{-1}) at the sites.

Total phosphorus deposition (P_{tot}) in bulk deposition varied between 0.07 and 0.29 kg ha^{-1} $year^{-1}$ with the highest value at SE14 Aneboda and lowest at SE16 Gammtratten. The stream water export rates reached 0.01-0.06 kg ha^{-1} $year^{-1}$ with the lowest value at SE15 Kindla.

Inorganic aluminum (Al_i), toxic to fish and other gill-breathing organisms, is analyzed in soil solution, groundwater, and surface waters at the IM sites. Relatively high total Al concentrations occurred in the soil solution (0.5–3.4 mg L^{-1}), and fairly high concentrations (3.4 and 1.5 mg L^{-1}, respectively) occurred also in groundwater in the recharge areas at SE04 Gårdsjön and SE14 Aneboda. The stream water Al_{tot}-concentrations were between 0.5 and 0.6 mg L^{-1} at the three sites with low pH (4.4-4.8). The Al_{tot} concentrations were lower, approximately 0.27 mg L^{-1} at the northern site SE16 Gammtratten with a pH of 5.6. Inorganic Al made up 27–60% of the total Al with the highest levels at low pH at SE15 Kindla and the lowest at SE16 Gammtratten, corresponding to 0.07–0.29 mg Al_i L^{-1}. According to the SEPA classification system, the Al_i concentrations at SE14 Aneboda and SE15 Kindla are considered *extremely high*, but *moderate* at SE04 Gårdsjön and SE16 Gammtratten.

The priority heavy metals Pb, Cd and Hg were still accumulating in the SE14 Aneboda catchment soils, while the stream concentrations were low compared with the levels causing biological effects. Only Pb had somewhat higher concentrations (1.3 mg L^{-1}) compared with the established limits for ecological effects. Methyl mercury (Hg_{Me}) concentrations, only measured at SE14 Aneboda, was still relatively high creating prerequisites for bioaccumulation. In stream water, the mean Hg_{tot} and Hg_{Me} concentrations were 11.2 ng L^{-1} and 1.1 ng L^{-1}, respectively. About 20% of the Hg_{tot} deposition was accumulated in the catchment soil. The 1.5 times higher concentrations of Hg_{Me} in stream water compared with in throughfall indicates ongoing methylation. SITES financed these heavy metal analyses.

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. At SE04 Gårdsjön, deposition is strongly influenced by input from the sea.

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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 ICP IM is to provide a framework to observe and understand the complex changes occurring in natural/semi natural ecosystems.

This report summarises the work carried out by the ICP IM Programme Centre and several collaborating institutes during the year since the previous annual report.

- A summary of previous data assessments
- A status report of the ICP IM activities, contents of the IM database, and geographical coverage of the monitoring network
- National Reports on ICP IM activities are presented as annexes. Contributing countries in this edition are Austria, Czechia, Estonia, Ireland, Russia, Spain and Sweden

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