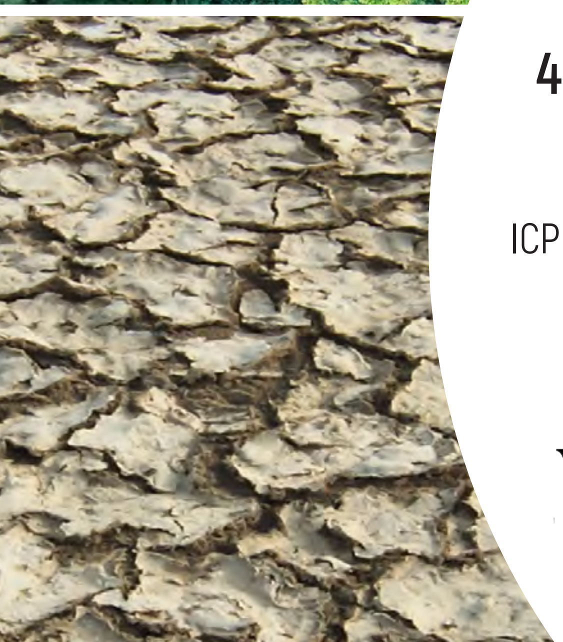
Federal Ministry of Food and Agriculture

UNECE

Convention on Long-range Transboundary Air Pollution



40 YEARS

ICP FORESTS

On the Pulse of European Forests

40 years of Pan-European Forest Monitoring: From Air Pollution to Climate Change

ICP Forests 40th Anniversary Report under the UNECE Convention on Long-range Transboundary Air Pollution (Air Convention)

wge Working Group on Effects of the Convention on Long-range Transboundary Air Pollution

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On the Pulse of European Forests

40 years of Pan-European Forest Monitoring:
From Air Pollution to Climate Change

ICP Forests 40th Anniversary Report under the UNECE Convention on Long-range Transboundary Air Pollution (Air Convention)

Marco Ferretti, Nathalie Cools, Michelle Lara Dörner,
Alexa Michel, Kai Schwärzel, Arne Verstraeten,
Peter Waldner (editors)

United Nations Economic Commission for Europe (UNECE)
Convention on Long-range Transboundary Air Pollution (Air Convention)
International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests)

http://icp-forests.net

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Statement by the UNECE Convention on Long-range Transboundary Air Pollution

Albena Karadjova
UNECE Convention on Long-range Transboundary Air Pollution, Secretary

Jesper L. Bak
UNECE Convention on Long-range Transboundary Air Pollution Working Group of Effects, Chairman

In the late 1960s, scientists discovered a connection between acid rain and forest dieback, fish loss in lakes, and more widespread effects on ecosystems, and it was realized that air pollution was not a local, but a regional-cross-border problem where pollutants could be transported thousands of kilometers away from their emission sources. This discovery led to the signing of the UNECE Convention on Long-range Transboundary Air Pollution in 1979, addressing the air pollution challenge on an international basis within the UNECE region.

The International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) was one of the first effects-related programs established under the Convention. The program was launched in 1985 in response to widespread public and political concern over extensive forest damage observed in Europe escalating in the early 1980s.

ICP Forests combines science and monitoring to support the development of cost-effective, effect-based policies to control air pollution in the UNECE region. Among its key contributions are the establishment of continuous data collection from two levels of forest health and ecosystem monitoring intensity, the establishment of research infrastructure in the 42 participating countries, and continuous improvement of quality assurance measures in the field, in laboratories, and in data management.

ICP Forests has made significant contributions to the progress of the Convention in improving the scientific understanding of the long-term effects of air pollution including sulphur and nitrogen deposition and ozone on forest health, growth, and biodiversity. The program, however, has produced numerous scientific and popularized publications.

Together with other programs under the Convention's Working Group on Effects (WGE), ICP Forests contributed substantially to the development of a framework for controlling and reducing the damage to human health and the environment caused by transboundary air pollution. As a result of the collective effort by the Parties to the Convention, emissions of a series of harmful substances in the region have been reduced by 40 to 80 percent. Countries' emission reduction commitments in the protocols under the Convention have successfully contributed to reduced emissions of specific pollutants, including over 80 percent reductions for sulphur, over 60 percent for nitrogen oxides, and 20 percent for particulate matter since 1990. The decrease in sulphur emissions has led to healthier forest soils even in the most polluted areas.

As the world is challenged by a triple planetary crisis with an urgent need to combat pollution, climate change, and biodiversity loss, the objectives of the ICP Forests remain as important today as they were 40 years ago. The unique combination of monitoring effects of anthropogenic (in particular air pollution) and natural stress factors on the condition and development of forest ecosystems in the region and of science contributing to a better understanding of cause-effect relationships will be equally important in the future.

We wish to congratulate all stakeholders on the achievements of the past 40 years and look forward to further successes in meeting the challenges ahead.

Statement by the editorial team of the Federal Ministry of Food and Agriculture, Germany

Extreme weather events such as heat waves, droughts, heavy rainfall, and storm events risk the vitality of forests. In Europe, the consequences of climate change can be seen in increased pest infestation and the uprooting of trees by heavy storms, to name but two. Forests and sustainable forest management make substantial contributions to climate change mitigation, support our sense of well-being and are important for ensuring biodiversity and providing a source of wood raw materials and secure jobs. It is therefore not surprising that interest in the state of European forests among scientists, politicians, and the general public is high.

In order to generate insights for present and future developments of European forests, it is necessary to continue harmonized transnational forest monitoring. With 40 years of shared expertise in international forest monitoring, ICP Forests, consisting of a network of 42 countries, is a pioneer in researching forest conditions in Europe if not worldwide. This is also reflected in the objectives of the program: While the initial focus was on investigating the effects of air pollution on the status of forests, ICP Forests now provides an ongoing overview of forest health, vitality, forest soil condition, and biodiversity in relation to air pollution, climate change, and other stressors. Through its long-term monitoring, ICP Forests supplies scientific insights into the impact of these stressors on forest ecosystem functions and provides services to policy makers and the general public.

The great success of ICP Forests is due on the one hand to its clear political mandate and on the other hand to the program structure established under the Geneva Air Convention with Germany as lead country, the Ministry representatives, the National Focal Centres, the Chair, the Programme Co-ordinating Centre, and the Expert Panels and Working Groups. This program structure not only regulates responsibilities and ensures participation and a transparent flow of information, but also ensures a high level of acceptance of ICP Forests in terms of environmental monitoring, knowledge gain, practical recommendations, and policy advice.

This Anniversary Report provides insights into the aims and structures of ICP Forests, the historical development of the program, the status and trends of European forests over the past 40 years, and scientific findings.

The German Federal Ministry of Food and Agriculture is proud of playing an important supporting role and invites everyone to celebrate the 40 years anniversary as part of the FORECOMON Conference and the Task Force Meeting in Dresden this year. The Federal Ministry of Food and Agriculture would like to take this opportunity to thank everyone who has contributed to the success, expertise, and development of ICP Forests and all those who will continue to do so in the future.

Enjoy reading it!
Your editorial team at the Federal Ministry
of Food and Agriculture, Germany

Statement by Marco Ferretti, Chair of ICP Forests

Forty years is a long time. It corresponds to about 50–75% of life expectancy, depending on where you are born; or a period as long as a career, in professional terms. It is also substantial for most of European forests, which are generally less than 80 years old (Forest Europe, 2020), and which have experienced significant environmental changes in the last 40 years.

For an internationally co-ordinated forest monitoring program, for which changes in both the human- (societal, political) and forest-related components are of obvious importance, to reach 40 years of activity is an exceptional achievement. I do not think I am wrong in saying that very few, if any, of those who met in Freiburg for the first session of the ICP Forests Task Force in October 1985 would have believed that the program could last for decades.

ICP Forests now celebrates its 40th anniversary. In this note I will not mention the results obtained so far. They are better reported and explained elsewhere in this report. Rather, I would express the mixture of feelings that came to me when looking back on the history of ICP Forests.

I feel that we, the ICP Forests community that was born and evolved since 1985, should be proud: We were pioneers, and that the forest monitoring science made progresses is also due to our efforts, success, and failures. We should then be humble and reflective: Our forests have taught us many lessons during these years. We should be visionary, to project and develop the ICP Forests in the next decades. For this, we should be aware: It is an immense effort to keep the program running, with hundreds of people involved across dozens of countries on a daily basis to maintain our plots, collect, and analyze samples, and observe how our forests develop. Then, we should be convincing, to obtain the support we need to keep watching our forests: monitoring costs – but "costs very little relative to the value of the resources it protects and the policy it informs" (Lovett et al., 2007).

Secretariat of the Air Convention, Task Force, European Commission, Lead country, Programme Co-ordinating Centre, Expert Panels and Committees, National Focal Centres with your national infrastructures and collaborators, colleagues that contributed your time and dedicated work: You made, make, and will make the ICP Forests. Many thanks for your enduring committment and support.

CONTENTS

Introduction: The Air Convention's journey in combating transboundary pollution

Michelle L. Dörner, Nathalie Cools, Arne Verstraeten, Peter Waldner, Kai Schwärzel

In the early 1980s, a worrying trend was observed, particularly in the forests of northern, central and eastern Europe: The tree crowns appeared severely defoliated, indicating a decline in tree vitality. Among other factors, scientists identified air pollution, caused by emissions from industries, power plants, agriculture, traffic, and domestic heating, as a possible reason for this development. As air pollution is not confined by national borders and can travel thousands of kilometers from its source, it quickly became a transnational concern. For forest ecosystems, pollutants such as sulphur dioxide, nitrogen oxides, and ground-level ozone can be particularly harmful. Once deposited on soil and vegetation, these substances can lead to acidification, excessive nitrogen enrichment (eutrophication), causing nutritional imbalances in trees and reduced growth and vitality.

From environmental decline to joint action

However, forests were by far not the only ecosystems affected by air pollution. Researchers had already begun to investigate this topic in the 1960s, when fish populations were decimated in acidified lakes. Building on the growing recognition of air pollution's negative effects, two conferences were held: the UN conference on the Human Environment (1972) and the Helsinki Conference on Security and Cooperation in Europe (1975). Both events paved the way for international discussions on collaborative efforts to reduce air pollution.

In 1979, such dialogues came to a head when 32 countries signed the UNECE Convention on Long-range Transboundary Air Pollution or Air Convention in Geneva. It was the first international treaty dealing with air pollution on a broad regional basis. Four years later, in 1983, the Convention came into force and since then serves as a common framework for transboundary co-operation on air pollution, which is now based on eight Protocols.

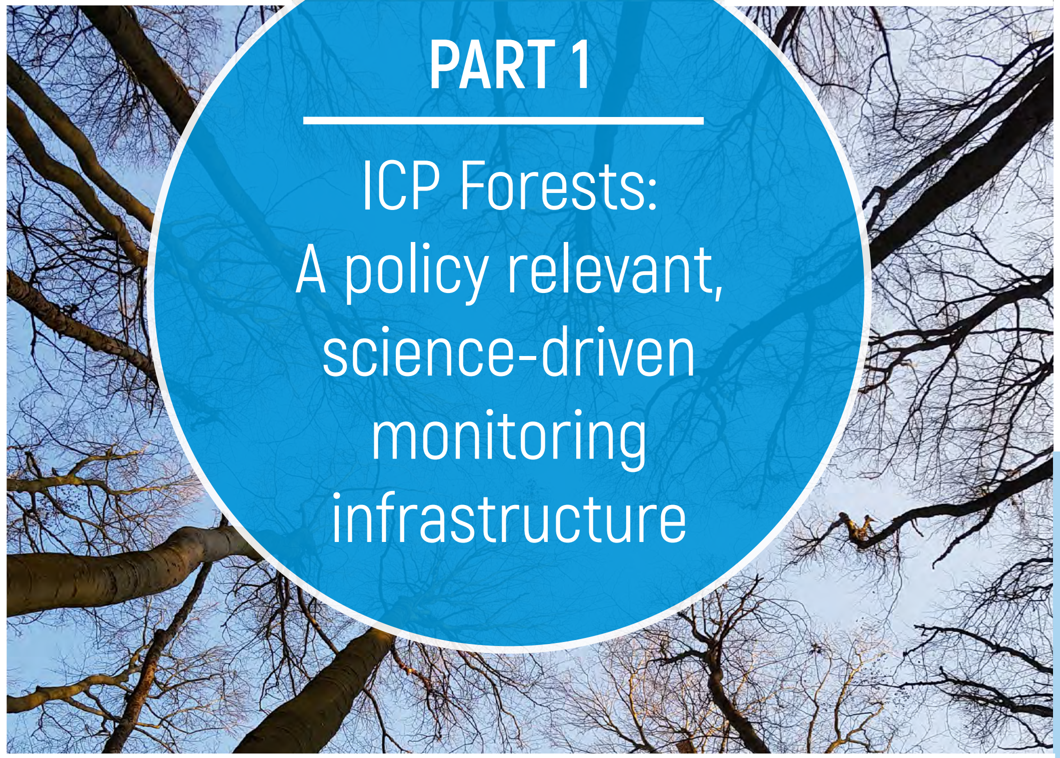
Among these is the Gothenburg Protocol of 1999 on the prevention of acidification, eutrophication, and ground-level ozone. It is special because it considers the negative effects of multiple pollutants, namely sulphur dioxide, nitrogen oxides, ammonia, volatile organic compounds, and ozone.

Cleaner air, but new challenges lie ahead

The Air Convention has already demonstrated significant success. With now 51 participating countries committed to cleaner air, joint efforts have led to substantial reductions in harmful emissions since 1990. Sulphur dioxide emissions have decreased by around 80%, while nitrogen oxides have been reduced by almost 60%. Additionally, emissions of fine particles have decreased by more than 40%, and significant progress has been made in curbing heavy metal pollution. Peak ozone levels have also declined in Europe and North America since the turn of the millennium.

Programs such as ICP Forests have been established to provide a framework for joint monitoring and reporting, which is necessary for providing the common understanding required to undertake air pollution reduction measures. These collective efforts have helped in reducing the pressure of air pollution on European forests. However, new challenges linked to e.g. climate change and its interaction with air pollution have emerged, highlighting the importance of continued international co-operation.

On the occasion of the 40th anniversary of ICP Forests, this brochure guides you through the development of the program (Part 1), presents scientific findings and trends from the community that illustrate the status of European forests over the past decades (Part 2), highlights key scientific insights as science stories (Part 3), and provides an outlook on the future of ICP Forests (Part 4).



PART 1

ICP Forests: A policy relevant, science-driven monitoring infrastructure

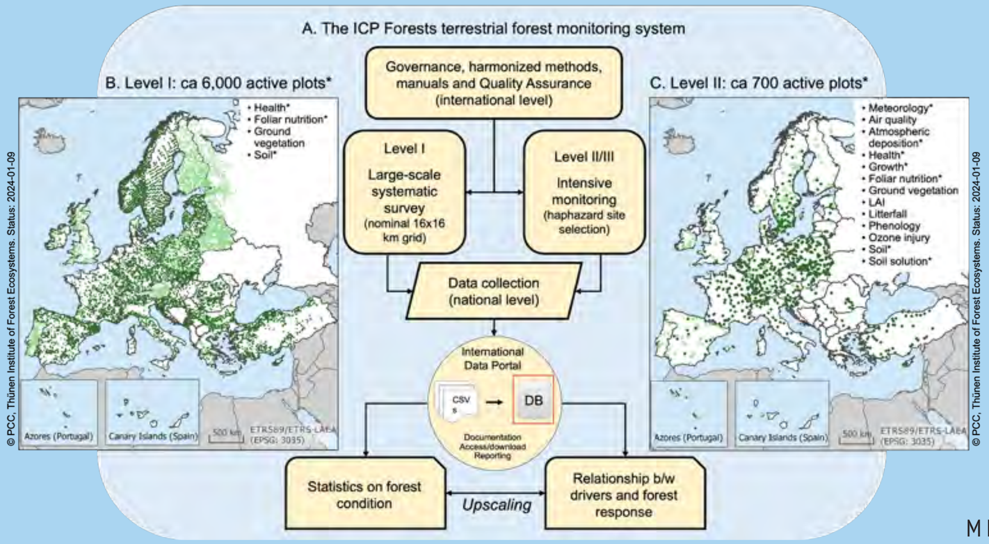
ICP Forests across 40 years of changes

Marco Ferretti, Kai Schwärzel

International forest monitoring is experiencing a renewed interest (Ferretti, 2021). The increasing pressure from climate change and climate change-driven disturbances has prompted a new series of initiatives to promote internationally harmonized forest monitoring systems (EC, 2023; Breidenbach et al., 2024; Ferretti et al., 2024; Wellbrock et al., 2024). This international and harmonized dimension is seen as essential due to the transboundary nature of climate change, forest-related interests, and the growing need for internationally comparable data. These concerns are not new. A similar situation arose in the 1980s in relation to another issue of transboundary nature (air pollution) and when extensive forest damage was observed in Central Europe, although the connection between the two was largely debated (Schütt and Cowling, 1985; Skelly and Innes, 1994; Kandler and Innes, 1995). During that period, an international harmonized forest monitoring system was not only advocated but also conceived and put in place. This system is the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests), and – after 40 years – is still operative.

Forest dieback at the German-Czech border, 1988, Revier Rauschenbach, Forstbezirk Marienberg, Ore Mountains.

Born international. The ICP Forests was conceived with an international focus. It received its mandate from the 1979 UNECE Convention on Long-range Transboundary Air Pollution (in short: Air Convention), the first legally binding multilateral international agreement to combat air pollution at the pan-European scale. The international origin of ICP Forests makes a huge difference when compared to other country-based systems because it forced immediate attention to ensuring data comparability at an international level. ICP Forests was officially launched on October 4, 1985, during the first Task Force Meeting in Freiburg (Germany). A few months later, in 1986, the European Union launched its Scheme on the Protection of Forests against Atmospheric Pollution (EEC, 1986), which provided essential co-financing for monitoring activities for more than 15 years.

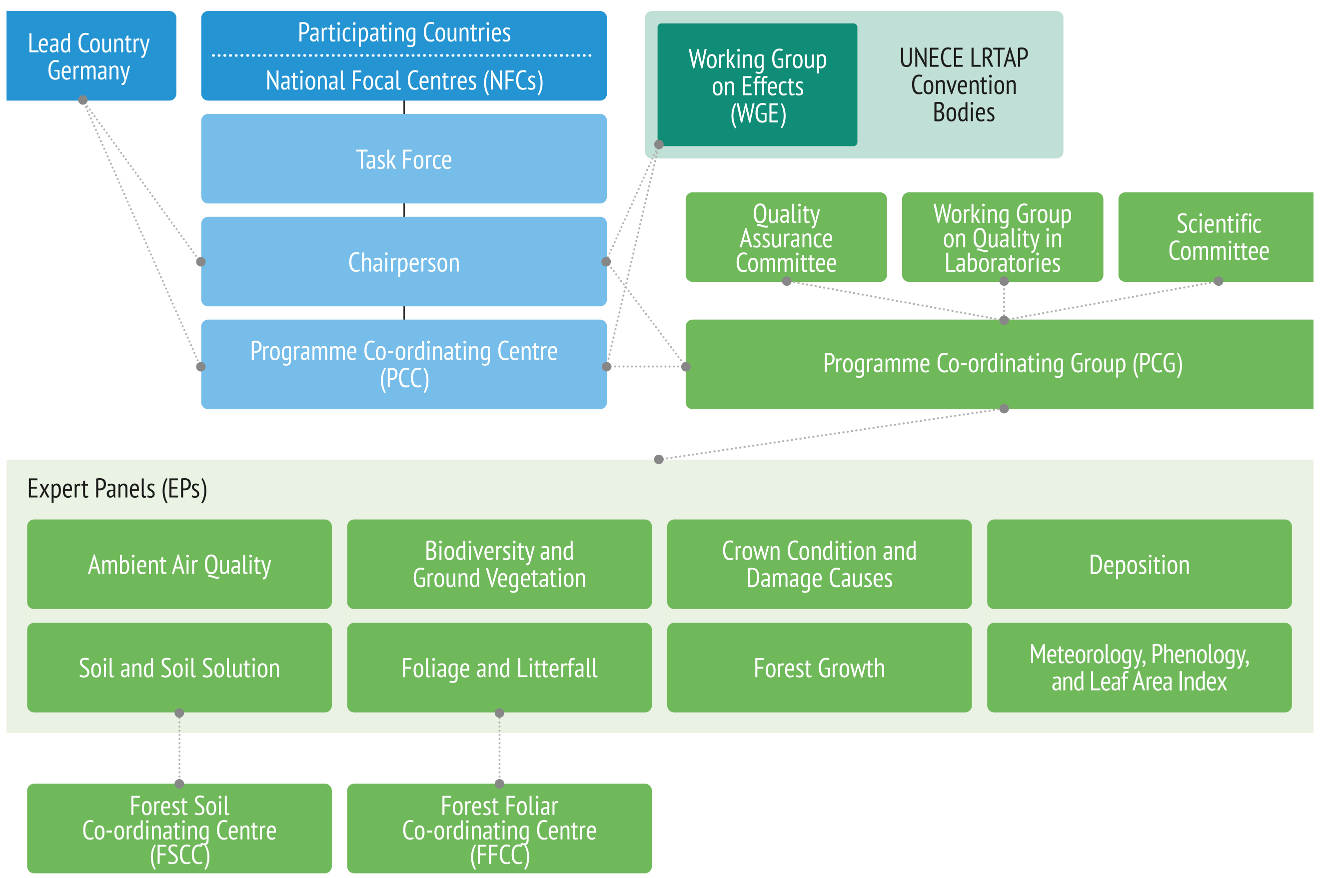


M Ferretti et al., 2024

The ICP Forests concept (A) is based on two differentiated monitoring levels, with two networks (B: Level I; C. Level II; dark green: active plots in 2022; light green: currently non-active plots) installed by participating countries (partly with the co-financing of the European Commission). Level I consists of approx. 6000 plots distributed according to a systematic transnational grid of 16 x 16 km (nominal density). There, tree health is evaluated annually according to a large set of attributes, while other investigations have been carried out on a more irregular and infrequent time basis (soil) or once only (foliar; diversity). Level II consists of approx. 700 intensive monitoring plots equipped with different combinations of measurement devices and located in selected forest ecosystems. There, measurements of biotic and abiotic drivers and forest ecosystem responses are co-located and permit investigation of the status and trends of several attributes and of driver-response relationships. Level I and Level II are connected by a common set of attributes measured according to the same methodologies. The system functions according to internationally harmonized methodologies for both Level I and II (see list of harmonized methods within each map) and nationally co-ordinated data collection. Asterisks identify networks/surveys/methodologies for which provisions have been published in the Official Journal of the European Union. All methodologies are available on the ICP Forests Website. Field data are validated at national and later at central level, used for reporting, and available upon request from the Programme Co-ordinating Centre (PCC).

Co-operatively developed. Since its establishment, the program has been developed co-operatively by the 42 participating countries and operated under an international governance in which all countries are involved. This governance combines a bottom-up science-based approach, where Expert Panels provide the scientific-technical basis for decision-making, with a top-down decision-making process, where the Task Force of ICP Forests makes official decisions based on the recommendations from the Expert Panels.

Ecosystem-oriented. From its early focus on the effects of air pollution on tree crowns, the scope of ICP Forests has expanded to include other ecosystem compartments (encompassing atmosphere, biosphere, geosphere, and hydrosphere), processes, and other environmental issues. New measurements have been introduced to assess the threats posed by climate change, the dynamics of carbon sequestration, and the provision of ecosystem services. The impact of environmental drivers on forest vitality, productivity, and biodiversity is increasingly reflected in the program's outputs. This progress has been possible thanks to the innovative design concept developed in the 1980s, which includes differentiated monitoring levels and accommodates a variety of monitoring activities. Today, the portfolio of measurements adopted by the ICP Forests allows for tracking changes in key forest ecosystem properties and processes. As a result, ICP Forests has remained relevant even when monitoring priorities have changed, as evidenced by the results presented in this report.



TGM Sanders

Large portfolio of attributes to monitor forest dynamics

Measurements at the ICP Forests plots include hundreds of variables to investigate the status and changes in forest health, diversity, productivity, and chemistry in response to a variety of biotic and abiotic drivers. Particular emphasis is now placed on air pollution, climate change, biotic damage and their interactions.

Quality assured. ICP Forests has been striving for a harmonized approach for data collection and processing across its two networks and all surveys. Ensuring data comparability has been a key priority since the program began. Intercalibration courses for field crews and ring-tests for laboratories were established at an early stage and are still carried out regularly. Methodologies for all surveys – such as sampling design, frequency of measurements, standards, assessment and measurement methods – are described in the ICP Forests Manual, which has been developed and continuously updated over the past 40 years (Ferretti et al., 2009). Each survey is subject to Quality Assurance (QA) and Quality Control (QC) measures, including training, intercalibration/cross-comparison courses, field checks, interlaboratory ring tests, data validation procedures, and internal reviewing (Ferretti and Fischer, 2013). This transnational harmonization and QA/QC approach makes ICP Forests unique in the global forest monitoring landscape. Quality-assured data are stored in a central database, managed according to an established data policy, and freely available upon request: There were approximately 350 data requests from all over the world over the past 10 years and over 650 scientific publications based on the ICP Forests infrastructure and/or data.

Development of ICP Forests

1985

Launch of ICP Forests at the 1st Task Force Meeting in Freiburg, Germany

Two Programme Co-ordinating Centres (PCC East and PCC West) were established in Prague and Hamburg, respectively

Start of the development of an **ICP Forests Manual**

1986

2nd Task Force Meeting in Freiburg, Germany

Adoption of the **ICP Forests Manual**

1st Crown Condition Surveys in accordance with the ICP Forests Manual in 20 participating countries

1987

1st Forest Damage Report of ICP Forests

1989

1st Report on the Health of Forests in the European Community 1987–1988

1992

1st Joint Report by the EU and ICP Forests, joint reporting continued until 2003

1994

1st Report on the ICP Forests Needle/Leaf Interlaboratory Test

1994/95

1st Soil Survey on more than 5000 Level I plots in 31 countries

1995

1st Foliage Survey on more than 1,395 Level I plots in 16 countries

1996

1st Transmission of Level II data to the **Forest Intensive Monitoring Co-ordinating Institute (FIMCI)** in The Netherlands

2010

First complete revision and harmonization of the **ICP Forests Manual** as part of the FutMon project

2011/12

Establishment of the Science Evaluation Committee (Scientific Committee from 2017 on) and **launch of the ICP Forests Scientific Conferences**

2013

Relocation of the Programme Co-ordinating Centre (PCC) from the Thünen Institute for World Forestry in Hamburg to the Thünen Institute of Forest Ecosystems in Eberswalde

Publication of the book **Forest Monitoring. Methods for Terrestrial Investigations in Europe with an overview of North America and Asia** authored and edited by the ICP Forests community

40 years of ICP Forests

2025

ICP Forests: Science and policy in a changing world

ICP Forests bridges science and policy through its approach to problem-solving, promotion of dialogue and openness to new demands.

Facts, not opinions: ICP Forests uses state-of-the-art monitoring approaches to produce high-quality data and information. From design to measurement methods and data collection, everything is thoroughly documented, accessible and traceable, and quality-assured. This transparency fosters confidence in our results and allows for credible answers to policymakers. The program's findings have been essential in addressing the scientific information needs of the Air Convention, documenting the success of air pollution abatement measures in Europe, the ongoing concerns, and the emerging challenges (see Part 2, Factsheets). Our data are also increasingly used by the scientific community (see Part 3, Science Stories). In addition, the data and information provided by ICP Forests are highly relevant to many national and international forestry and environmental bodies and processes.

Science to promote dialogue and co-operation. Another way to look at the link with policy and science is the role of ICP Forests in promoting dialogue across countries and institutions at national and international level. One of the program's greatest achievements has been demonstrating the feasibility and effectiveness of transnational forest monitoring (Ferretti and Fischer, 2021). ICP Forests started in the mid-1980s and developed throughout the following decade, during a phase of dramatic political changes in Europe. Despite this political instability, co-operation within the monitoring program has grown and expanded. Several factors contributed to this: the politically neutral framework provided by the Air Convention; the strong political commitment from the European Commission (originally from DG Agriculture, then from DG Environment), which led to an unusually long-term support and to a joint reporting from 1992 to 2003, with cascading effects on non-EU countries; and the outstanding commitment, perseverance, and motivation of hundreds of scientists, foresters, and national funding agencies. In the past twenty years, ICP Forests has also fostered co-operation with other long-term monitoring networks in Europe, North America, and Asia, and dialogue is ongoing with experts from South America.

Science to address new demands. A third key aspect of ICP Forests is its ability to evolve and address emerging environmental issues of international and global relevance. Thanks to its multi-level, integrated design concept, ICP Forests has been able to incorporate research questions not only from the Air Convention (1979) but also from Forest Europe (1990, formerly the Ministerial Conference for Protection of Forests in Europe – MCPFE), the Convention on Biodiversity (1992), the Kyoto Protocol (1998), the European Union National Emission Ceiling (NEC) Directive (2016), and the Paris Agreement (2016). The program's structure, design, portfolio of measured variables, and governance have remained flexible and adaptive, ensuring its continued relevance. This adaptability can provide a solid foundation for the future of EU forest monitoring systems, such as the one suggested by the European Commission (EC, 2023).

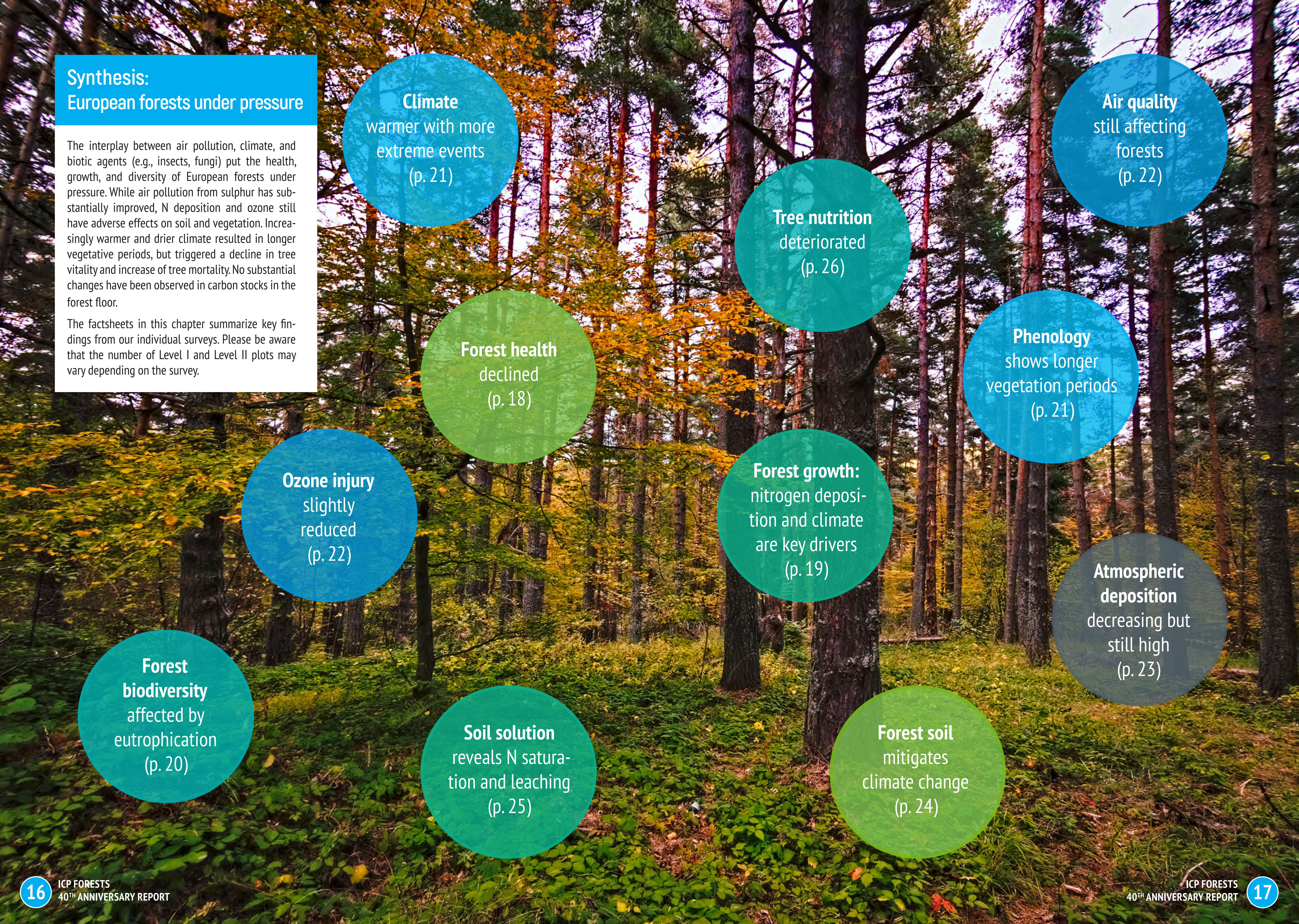
ICP Forests and the European Commission: decades of co-operation

There is a long history of co-operation between ICP Forests and the EC. First, the European Union is a signatory to the Air Convention. Second, through the series of regulations beginning with the Reg. 3528/86, subsequent ones (Forest Focus) and programs (Life+ FutMon), the EC co-financed the installation of Level I and Level II plots and monitoring activities in EU Member States almost continuously until 2011. Third, ICP Forests and EC had a joint reporting system from 1992 to 2003. The figure shows the first joint Forest Condition Report published in 1992. Dialogue to foster further co-operation is still ongoing.

ICP Forests today: A model for the future of international forest monitoring

Today, the vision of ICP Forests is for an "European-wide forest monitoring infrastructure, integrating multiple levels and providing high quality, transparent, robust, and FAIR open access data (i) on the status and trends of forest health, vitality, productivity, and biodiversity; (ii) on risks of forests being exposed to anthropogenic and natural stressors (separately and combined), and (iii) on progress in achieving relevant policy goals to diminish risks" (Schwärzel et al., 2022).

At a time of growing concern on the future of our forests and of a demand for a common, harmonized monitoring system, we believe that its vision, international and co-operative nature, ecosystem-oriented approach, enduring emphasis on quality assurance and accessible data, and – last but not least – its 40 years of experience, make ICP Forests not only a successful story but also a useful model for the future, pan-European forest monitoring.



Synthesis: European forests under pressure

The interplay between air pollution, climate, and biotic agents (e.g., insects, fungi) put the health, growth, and diversity of European forests under pressure. While air pollution from sulphur has substantially improved, N deposition and ozone still have adverse effects on soil and vegetation. Increasingly warmer and drier climate resulted in longer vegetative periods, but triggered a decline in tree vitality and increase of tree mortality. No substantial changes have been observed in carbon stocks in the forest floor.

The factsheets in this chapter summarize key findings from our individual surveys. Please be aware that the number of Level I and Level II plots may vary depending on the survey.

Climate
warmer with more extreme events
(p. 21)

Air quality
still affecting forests
(p. 22)

Tree nutrition
deteriorated
(p. 26)

Forest health
declined
(p. 18)

Phenology
shows longer vegetation periods
(p. 21)

Ozone injury
slightly reduced
(p. 22)

Forest growth:
nitrogen deposition and climate are key drivers
(p. 19)

Atmospheric deposition
decreasing but still high
(p. 23)

Forest biodiversity
affected by eutrophication
(p. 20)

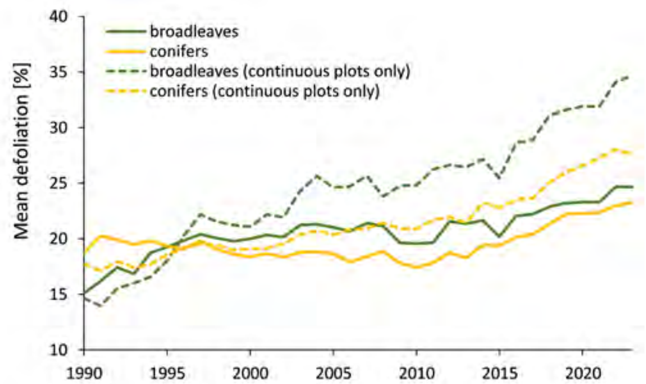
Soil solution
reveals N saturation and leaching
(p. 25)

Forest soil
mitigates climate change
(p. 24)

Tree health is deteriorating in the European forests

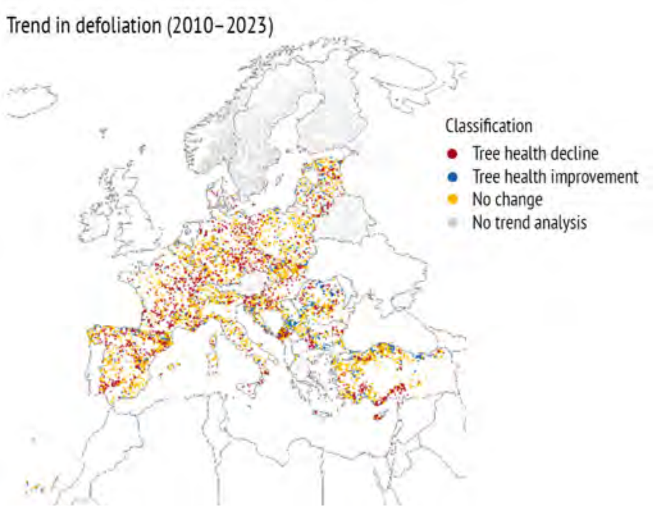
Volkmar Timmermann, Nenad Potočić, Anne-Katrin Prescher

The crown condition survey was the first established under the program, starting in the mid 1980s. Since then, a total of 36 countries have collected data through the pan-European ICP Forests Level I monitoring network. Installed on a 16 x 16 km grid, the network covers the most important climatic gradients, biogeographical regions, and air pollution levels in Europe. Annual tree condition assessments are currently carried out on around 110,000 trees from more than 130 species on approximately 5,600 forest plots. The tree crown condition survey is also carried out on Level II plots.



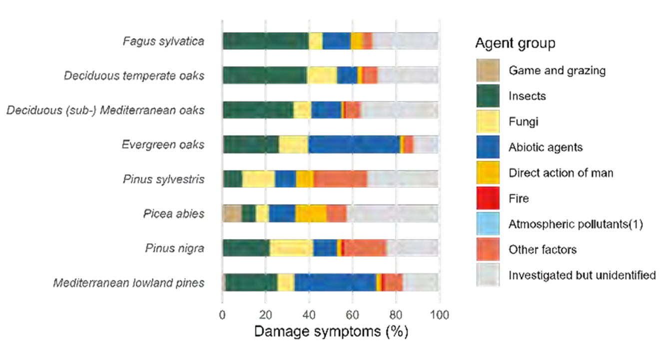
Long-term development of defoliation

Mean defoliation for both broadleaved species and conifers has increased since 1990. This increase has been more prominent for broadleaves than for conifers, and even more for the eight countries with continuous data coverage. However, since 2010, defoliation of conifers has also increased substantially. Although many stress factors influence tree crown condition, this development points to changing environmental conditions in Europe as a possible cause.



Tree health is declining all over Europe

From 2010 to 2023, there was a decline in tree crown condition on 33.7% of the plots, while an improvement was observed on only 10.7% of the plots. On 55.6% of the plots, no statistically significant change was found. A decline in tree health was observed all over Europe, indicating that global change influences tree health along with regional and local conditions.



Main causes of forest damage in Europe

In the period 2012–2023, the most important categories of damaging agents have been insects (26% on average), abiotic factors (16%), and fungi (11%). Defoliators, drought, and decay/root rot have been the most prominent single factors within each agent group. The observed impact of damaging factors was found to be species-specific. This information is essential for future forest management.

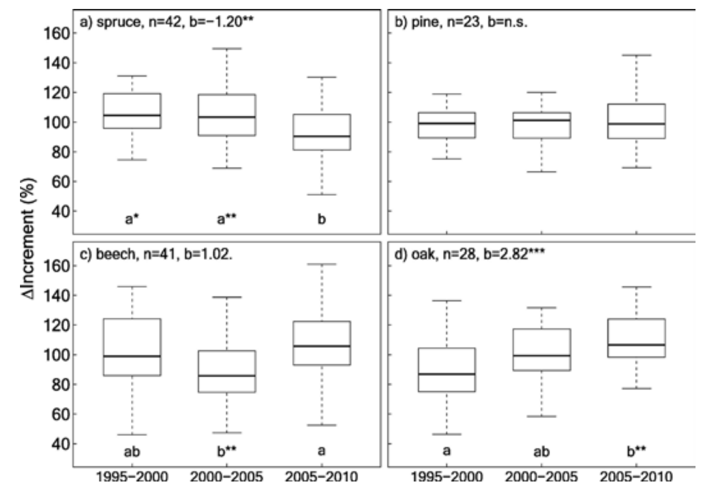
Multiple factors affect forest growth

Tanja Sanders, Andrei Popa, Monika Vejpustková,

The growth of trees is one of the main indicators of forest condition and integrates the reaction of trees to changing environmental conditions. Measurements at ICP Forests Level II plots enable a Europe-wide assessment of species growth, adaptive processes, and species interactions with environmental factors across diverse climate, soil, and air pollution conditions.

Strengthening resilience to global change

Uneven-aged mixed forests are proposed as a strategy to enhance resilience, as their diverse structure can better withstand variable conditions due to greater adaptability. The combination of species with varying growth patterns and water use efficiencies could help buffer against the uncertainties in climate projections and ensure more stable forest productivity over time.



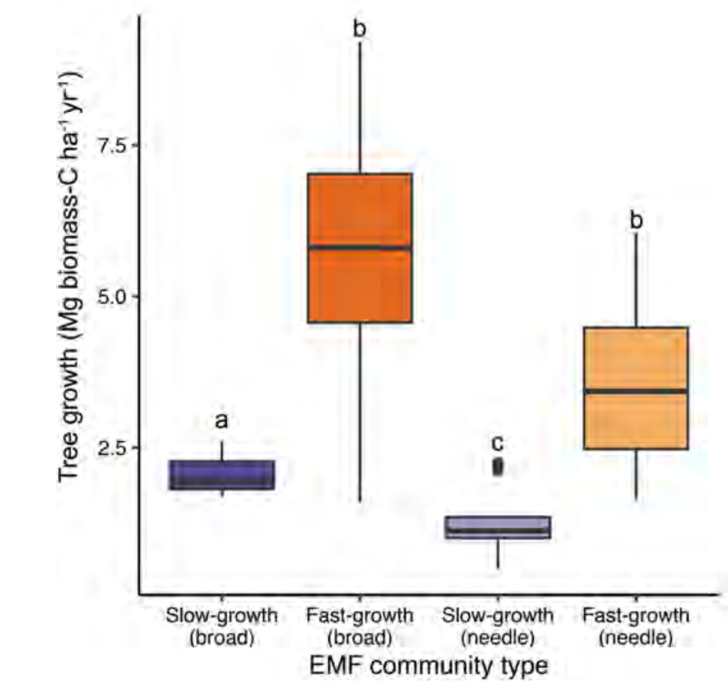
Etzold et al., 2020

Interactions between growth and the environment

All the investigated species show specific and often complex relationships between tree growth and environmental variables, with nitrogen (N) deposition being a key driver and at least as important as climate. N deposition does not always directly affect foliar N.

Species-specific climate responses

Correlations to temperature and precipitation vary between species and regions but with a trend across all species of increased growth linked to higher mean temperatures. Precipitation increases the growth of spruce and pine trees.



Anthony et al., 2022

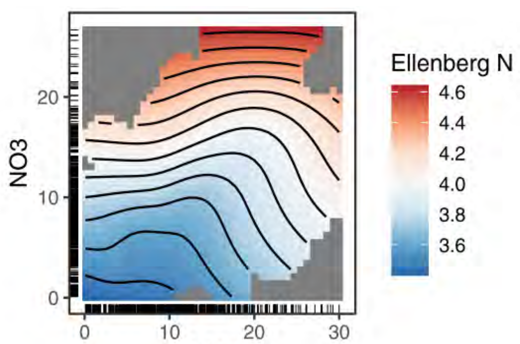
Mycorrhiza impact growth

Ectomycorrhizal fungal (EMF) communities strongly impact tree growth, influencing forest productivity and carbon (C) storage. Fast-growing forests harbor inorganic N specialized EMF communities, while slow-growing forests are enriched in organic N specialists.

Biodiversity and ground vegetation in Europa are affected by nitrogen deposition and climate change

Leena Hamberg, František Máliš

The composition and structure of vegetation are important factors for assessing the biological diversity of forest ecosystems. It influences a number of ecosystem processes and interacts strongly with other biotic components (insects, game, etc.), as it is a determinant habitat for many species. Vegetation has also been identified as a specific target for the calculation of critical loads/levels. ICP Forests monitors the diversity of ground vegetation and epiphytic lichens at its Level II plots.



Weldon et al., 2022

Nitrogen deposition causes a shift in bryophyte communities

In forest bryophyte communities in central and northern European forests, nitrophilic species benefit at the expense of N-sensitive species (Weldon et al., 2022).

Eutrophic vascular plant species are replacing oligotrophic ones

Eutrophic vascular plant species (i.e. species associated with nutrient-rich sites) are replacing oligotrophic ones (i.e. species associated with nutrient-poor sites) across Europe where nitrogen deposition exceeds critical loads for vegetation (Dirnböck et al., 2014).

Climate change affects plant species within their climatic niche

Temperature, precipitation, and duration of snow cover explain plant species occurrences over time and their movement poleward (Antão et al., 2022).

Data quality is crucial for monitoring

When assessing ground vegetation, observer error should be carefully taken into account. It can be controlled by harmonized methods, training, and inter-calibration (Seidling et al., 2020).

Forest meteorology and phenology reveal increased temperature and extended vegetation period

Lothar Zimmermann, Stephan Raspe, Stefan Fleck

Trends of meteorological variables influence the structure, growth, health, and stability of forest ecosystems. Climate change is altering the occurrence and frequency of drought events, storms, and floods, and the response of forest trees. ICP Forests monitors meteorology and phenology at Level II plots.

A gap-filled and quality-checked European forest meteorological dataset

ICP Forests compiled a gap-filled, harmonized, and quality-checked long-term dataset of daily forest meteorological observations. The dataset includes daily meteorological data from 477 mostly open-field stations originating from 29 countries for the period 1990–2022.

Marked temperature increase due to climate change

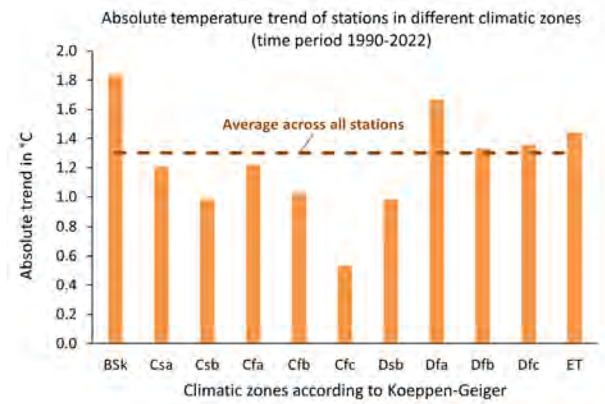
During the period 1990–2022, the annual air temperature increased at all stations by an average of +1.3 °C. Trends differed between the climatic zones: The largest changes were observed in the cold semi-arid climate (Bsk) and the smallest in the temperate cold-summer oceanic climate (Cfc).

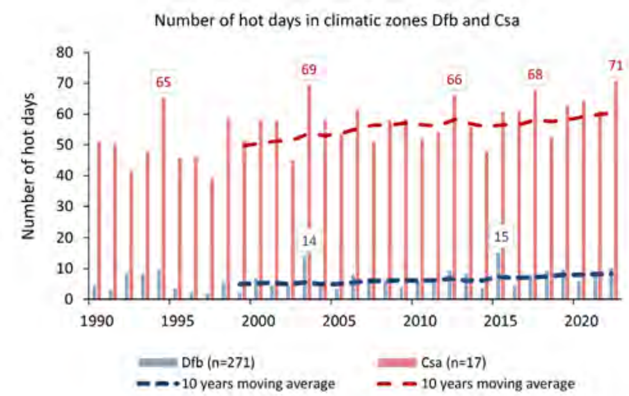
Heat extremes increased strongly in hot Mediterranean climate

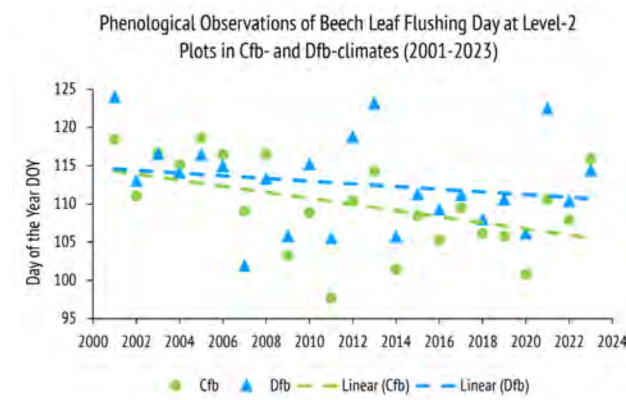
The number of hot days (Tmax ≥ 30°C) increased in the hot-summer Mediterranean climate (Csa) by 14.7 days, while the colder central European Dfb climate showed a rise of 4.0 days. Extreme years with a hot summer drought were more frequent in the Csa climate than in the more temperate Dfb climate.

Prolongation of vegetation period

Due to temperature increase, budburst occurs earlier in the year, thereby extending the vegetation period. The figure illustrates this trend for 57 beech stands on ICP Forests Level II plots between 2001 and 2023 in two different climate zones. In the oceanic Cfb climate, leaf budburst starts on average 8.8 days earlier, and in the more continental Dfb climate 3.9 days earlier.



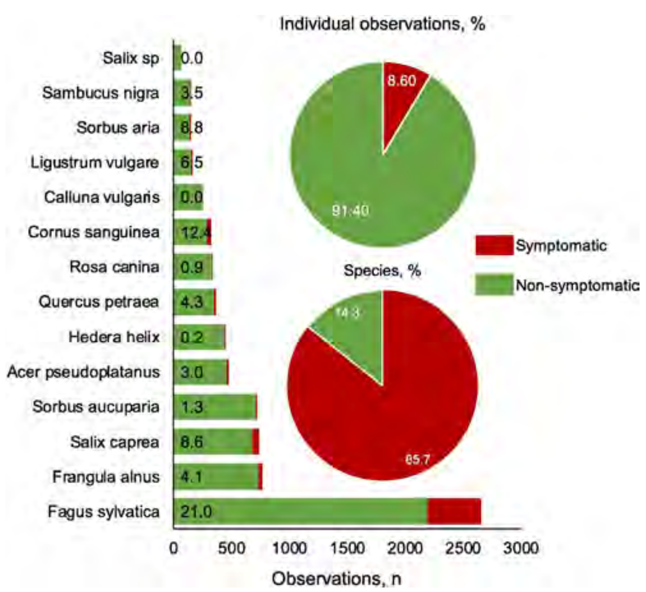


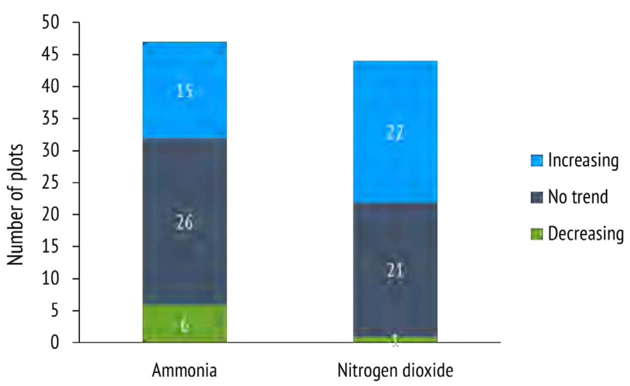


Ambient air pollution still affects European forests

D Pitar, E Gottardini, M Ferretti, M Schaub, V Calatayud, M Häni, V Araminiene, V Buriánek, S Cecchini, L Dalstein, I Hůnová, T Jakovljević, K Kaoukis, G Kardinov, J Neirynck, M Nicolas, A-K Presher, R Novotný, H Pavlendova, N Potočić, M Rupel, A Russ, V Stakėnas, A Verstraeten, P Vollenweider, D Zlindra

Air pollution can have adverse effects on vegetation at different levels: cellular, foliar, plant, community, and ecosystem. ICP Forests monitors air pollution levels (ozone, ammonia, nitrogen dioxide) and the visible effects of ozone on a selection of Level II plots across Europe.





Ozone levels across European forests

From 2005 to 2018, ozone (O_3) levels were assessed across 20 countries. On average, O_3 levels decreased from 43 to 35 ppb (Ferretti et al., 2024).

The ‚fingerprint' of ozone on forest vegetation

Ozone visible injuries were frequently observed in sensitive species, with a slight decline aligning with lower ambient ozone levels. Despite high ozone levels, Mediterranean species showed fewer symptoms. Alpine and Continental Europe face higher ozone risk. Quantification of the potential impact of ozone requires observation of the entire plant community at a given site. (Ferretti et al., 2024)

Nitrogen in forest air

Nitrogen dioxide (NO_2) concentrations, measured in 44 plots across Europe during 2005–2020, increased in half of the plots. Air concentration of ammonia (NH_3), measured in the same period in 47 plots, increased on 15 plots. (Pitar et al., 2023)

Atmospheric deposition in European forests shows differentiated reduction trends

A Verstraeten, A Schmitz, B Ahrends, N Clarke, W de Vries, K Hansen, C Hilgers, C Iacoban, T Jakovljević, PE Karlsson, T Kirchner, A Marchetto, H Meesenburg, G Pihl Karlsson, A-K Prescher, A Thimonier, P Waldner

Atmospheric deposition is an important source of macro- and micronutrients to forest ecosystems that are key to forest health, growth, and diversity. But excess input from deposition may cause eutrophication and acidification of forest ecosystems. ICP Forests monitors atmospheric deposition in open field as well as under the forest canopy on its Level II plots.

Declining sulphate deposition

Acidifying non-marine sulphate deposition has decreased substantially (>60%) in forests across Europe over the past two decades. The map on the right shows the mean annual throughfall (TF) deposition rates and trends of non-marine sulphate in forests across Europe for plots with at least 5 years of data between 2000 and 2020. With no doubt, the strong reduction in SO_2-emissions is a great achievement of the UNECE Air Convention.

Nitrate and ammonium decreased less

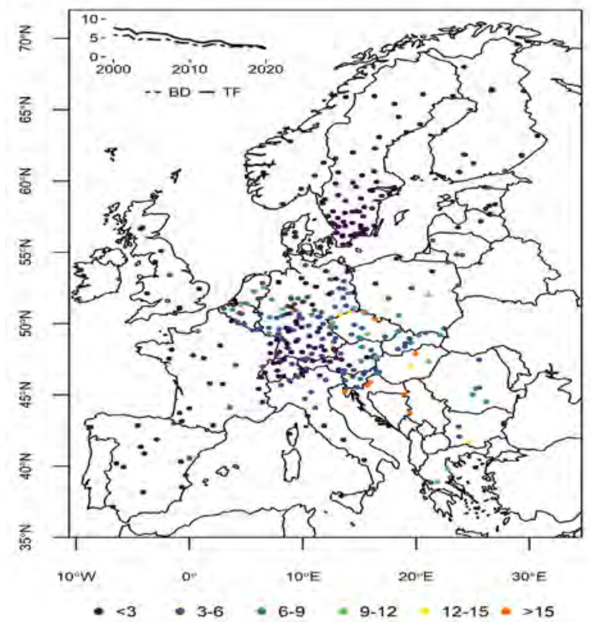
Deposition of nitrate and ammonium has decreased to a lesser extent than sulphate. In the last decade, a stagnation or even a re-increase has been observed in several European forests, particularly for ammonium.

Total deposition of inorganic N is highest in central Europe

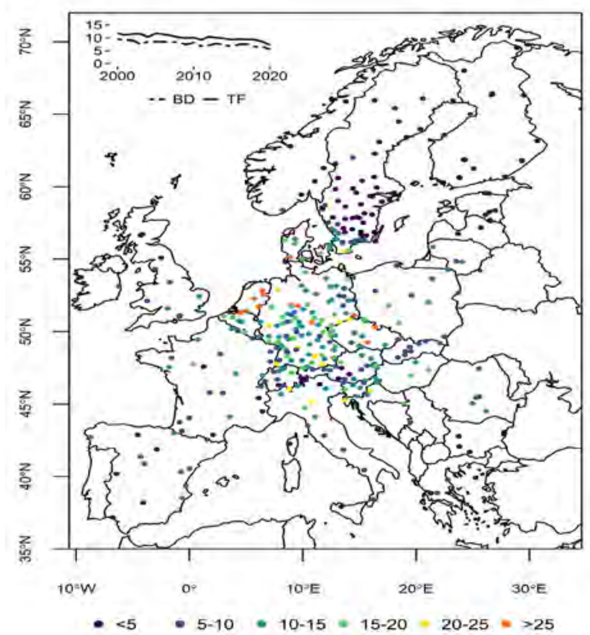
Total inorganic N deposition is highest in central Europe. The critical load for an increased risk of eutrophication is still exceeded in most forests in Europe.

Slightly decreasing deposition of base cations

The decreasing trend in acidifying sulphate and nitrogen throughfall deposition was accompanied by a simultaneous decrease in the deposition of neutralizing base cations (calcium, potassium, and magnesium).



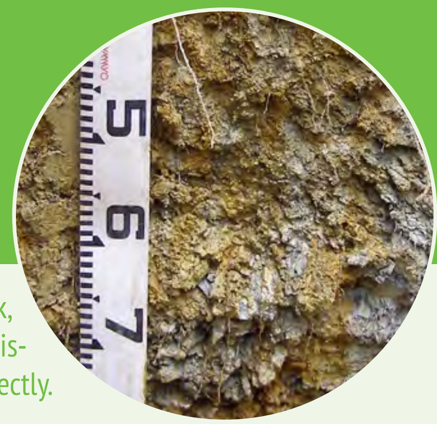
Color classes and trend lines indicate annual deposition rates in kg of **sulphur** per hectare per year.



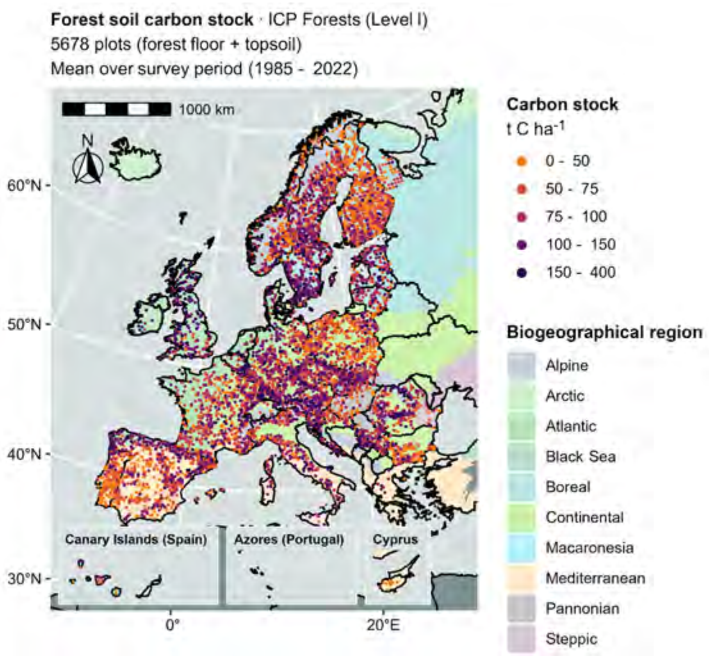
Color classes and trend lines indicate deposition rates in kg of **nitrogen** per hectare per year.

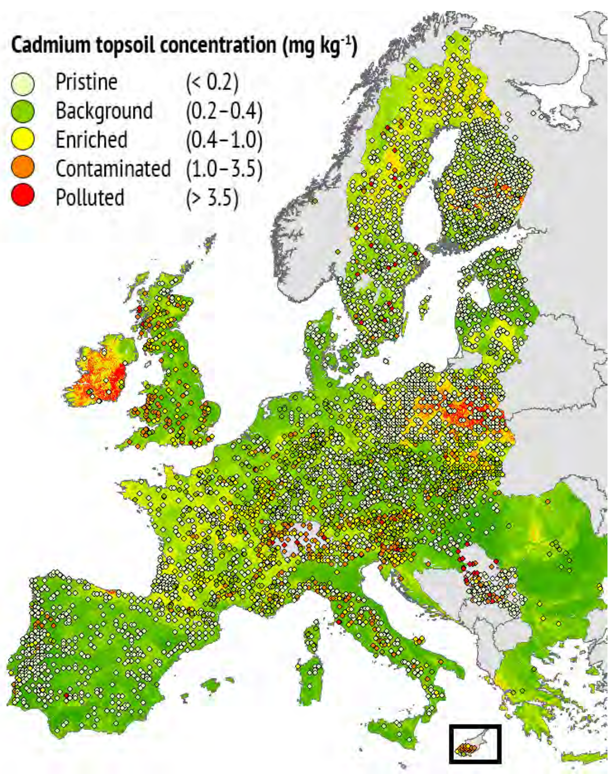
Forest soils between air pollution and climate change

Nathalie Cools, Heleen Deroo, Bruno De Vos



Forest soil characteristics are driven by a number of factors: parent material, bedrock, topography, climate, vegetation, living organisms, and natural and anthropogenic disturbances. Air pollution and climate change also affect forest soils directly or indirectly. ICP Forests monitors forest soils in the Level I and Level II plot networks.





European forest soils are contributing to climate mitigation

On average, European forest soils store between 15 and 17 tonnes of organic carbon per hectare in the forest floor and between 91 and 113 t C.ha^{-1} in the mineral soil. Forest soil carbon stocks in the Mediterranean, Continental, and Pannonian regions are lower than those in the Alpine and the Boreal regions, while the highest stocks are found in the Atlantic region. Overall, no significant changes in carbon stocks have been detected over time in the forest floor, though stocks tend to increase in the mineral soil and tend to decrease in peat soils.

Heavy metals in forest soils

The concentrations of cadmium, zinc, nickel, chromium, copper, lead, and mercury were determined in the forest floor and mineral soil layers. As an example, the map on the left shows cadmium (Cd) concentration levels in the mineral topsoil of 4,849 forest sites plotted on the LUCAS 2009 cadmium map (Ballabio et al. 2024) highlighting contamination hotspots. On 6.9% of ICP Forests sites the threshold of 1 mg Cd kg^{-1} is exceeded compared to 5.5% of the 2009 LUCAS points (all landuses). Approximately $^{2}/_{3}$ of all sites show very low Cd levels (< 0.2 mg kg^{-1}), 15% of the sites are within the range of natural background levels, and 11% are considered enriched, while 8% are contaminated and 1% are really Cd polluted.

Soil Solution is key to understanding nutrient and pollutant fluxes in forest ecosystems

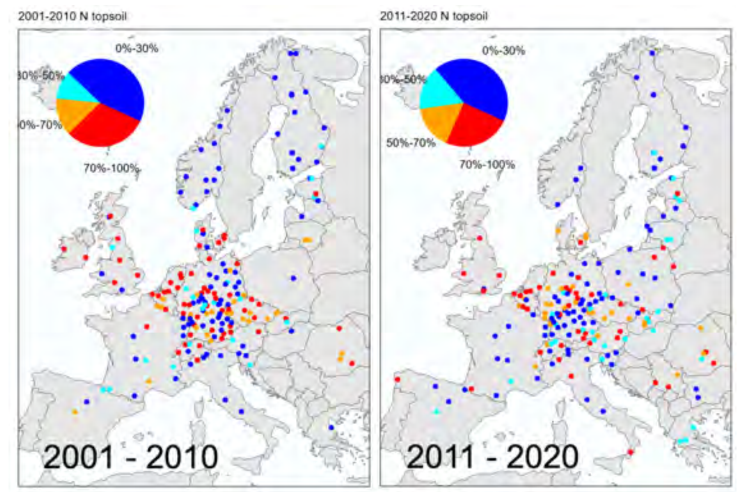
Tiina Maileena Nieminen, Peter Waldner, Katrin Meusburger, Bruno De Vos, Nathalie Cools

The chemical composition of soil solution indicates nutrient availability to forest plants, as well as pollutants and their movement into water bodies. Analyses of soil solution have been carried out for decades at the ICP Forests Level II plots according to harmonized methodologies.

Nutrient imbalances

High nitrogen (N) emissions lead to elevated nitrate (NO_3^-) concentration in soil and water, causing nutrient imbalances that harm forest and water ecosystems. Updated information is essential to favor policies aiming at reducing eutrophication. Empirical critical limits (Iost et al., 2011) were set for NO_3^- in relation to nutrient imbalances for tree species, N saturation, and NO_3^- leaching from the forests.

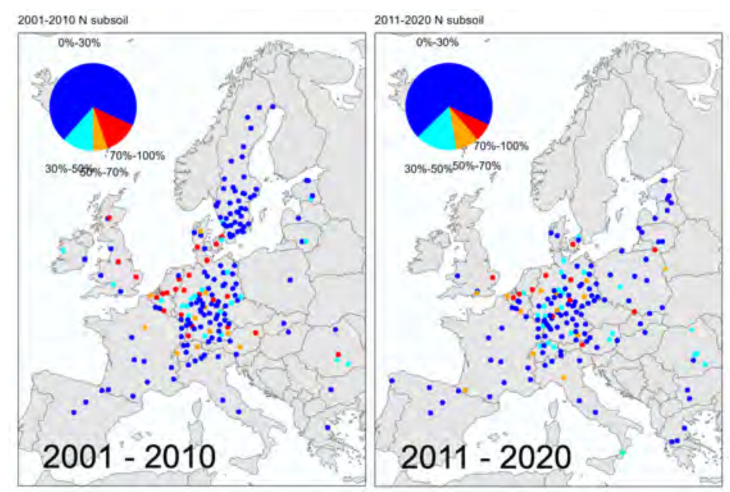
Almost half of the plots had a high rate of nutrient imbalances in the period 2001–2010, with a slight decrease in 2011–2020. These plots cover much of Europe, excluding only the Fennoscandian area and the Baltic countries in the latter decade.



Exceedance of tree-specific critical limits for N in soil solution in 0-40 cm depth regarding nutrient imbalances (percentage of samples)

Nitrogen saturation and leaching

The number of plots with frequent critical limit exceedances (>50% of samples) for soil nitrogen saturation and nitrogen leaching to ground and surface waters was clearly lower than those for nutrient imbalances. In addition, there was a decrease between 2001–2010 and 2011–2020 in the frequency of plots of the category with the highest share of exceedances (>70% of samples).

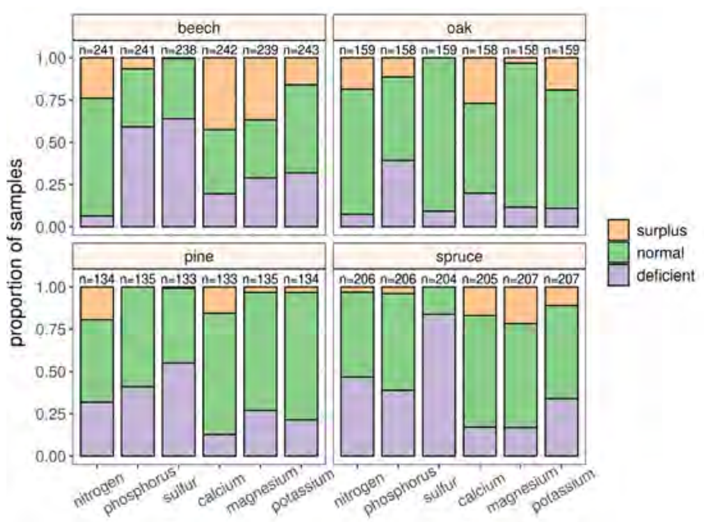


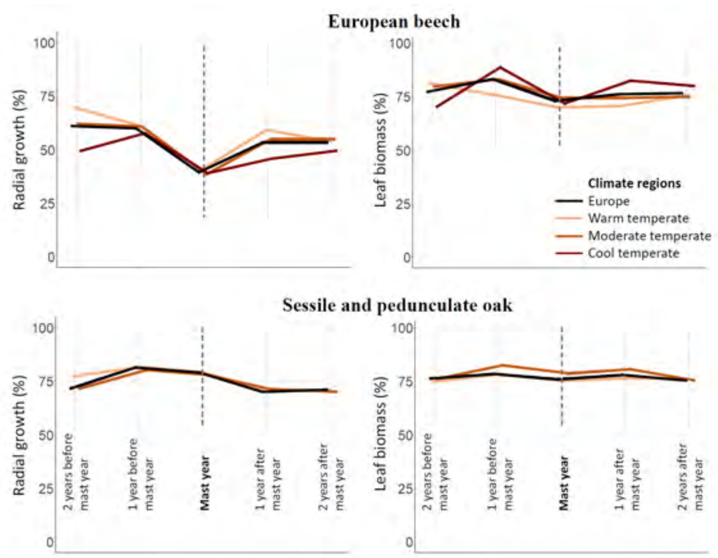
Exceedance of critical limits for N in soil solution regarding nitrogen saturation in subsoil (percentage of samples)

Tree foliage and litterfall reveal declining tree nutritional status and improve the assessment of carbon dynamics

L Wohlgemuth, M Neumann, M Jonard, L Ukonmaanaho, P Rautio, A Nussbaumer

Nutrient supply and balance are essential for healthy forests. Analyses of foliar nutrients can reveal nutrient deficiencies and/or toxicities and can indicate a biological response to environmental changes. ICP Forests monitors the nutritional status of forest trees in Level II plots.





Decline of nutritional status of European forest trees

Analysis of overall trends reveals significant declines in foliage concentrations of several nutrients in the main European forest tree species. Such declines in foliar nutrients may lead to nutritional deficiencies (see bar graph on the left). (Jonard et al., 2015; Talkner et al., 2015; Braun et al., 2020; Peñuelas et al., 2020; Du et al., 2021).

Improvement of the estimation of carbon and nutrient fluxes to forest soils

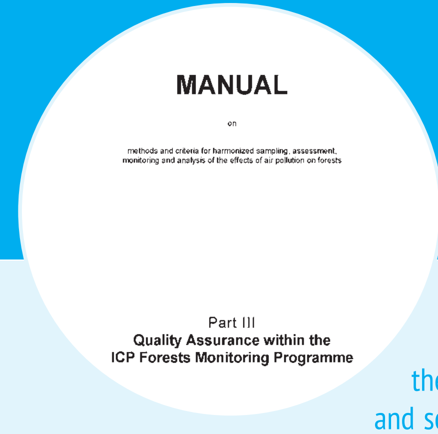
More than 1,600 ICP Forests annual litterfall observations form the basis for modelling litterfall carbon and nutrient fluxes. The total annual amount of carbon, nitrogen, phosphorus, and potassium transferred to European forest floors via litterfall has been estimated to be 351 Tg, 8.2 Tg, 0.6 Tg, and 1.9 Tg, respectively. (Neumann et al., 2018)

Mast years and resource dynamics

With annual litterfall data, we can identify spatially synchronized high fruiting years (mast years). During those years, radial growth of tree stems and leaf biomass decreases in beech. In contrast, oak species exhibit no change in vegetative growth. (Nussbaumer et al., 2021)

An overall quality assurance perspective for ICP Forests

Manuel Nicolas, Marco Ferretti


MANUAL

on

methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests

Part III

Quality Assurance within the ICP Forests Monitoring Programme

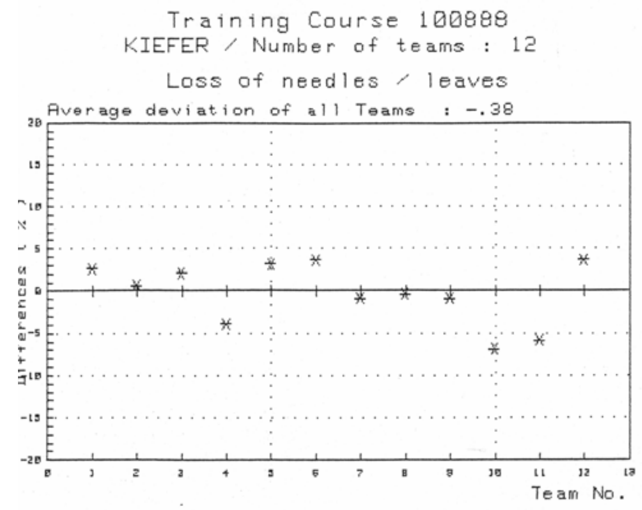
Data quality is essential in forest monitoring. Efforts have been made to improve data quality since the early stages of ICP Forests: e.g. the ICP Forests Manual and the international crown condition intercalibration courses were initiated in 1986–1987 and soil inter-laboratory comparisons started in the 1990s. Later, a great deal of activity was developed, with particular emphasis on laboratory analyses and intercomparison.

A committee created for the overall quality assurance of the program

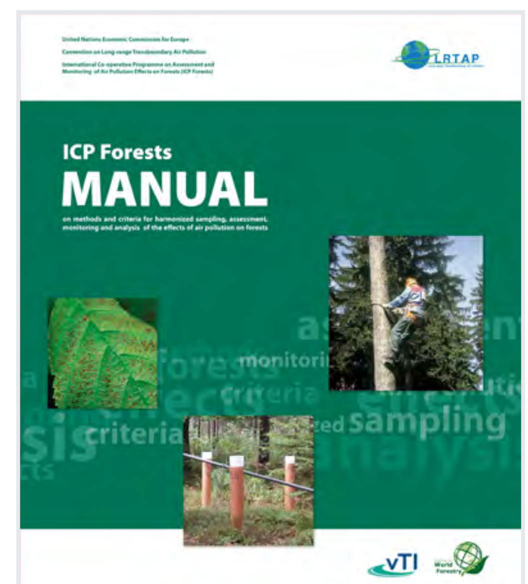
The Quality Assurance (QA) Committee was created in 2007 to promote data quality and to properly define a common approach within ICP Forests. Within a 3-year mandate until 2010, the Committee led the review of all parts of the ICP Forests Manual according to harmonized rules and elaborated a new Manual part about QA (Ferretti et al., 2021).

A manual to be continually improved and adapted to new situations

The QA Committee was convended again in 2020 to review the QA Manual Part and develop further guidelines, especially to harmonize the reporting of quality measures in all surveys. Initially, the ICP Forests Level II programme was designed for plots installed in adult and homogenous forest stands. But after more than 30 years of monitoring, additional instructions were required in how to deal with stands under regeneration after final cutting or those severely damaged by natural disturbances (storms, bark beetle attacks, etc.). The ICP Forests Manual is being further developed regularly to provide guidance in these situations (Ferretti et al., 2020).



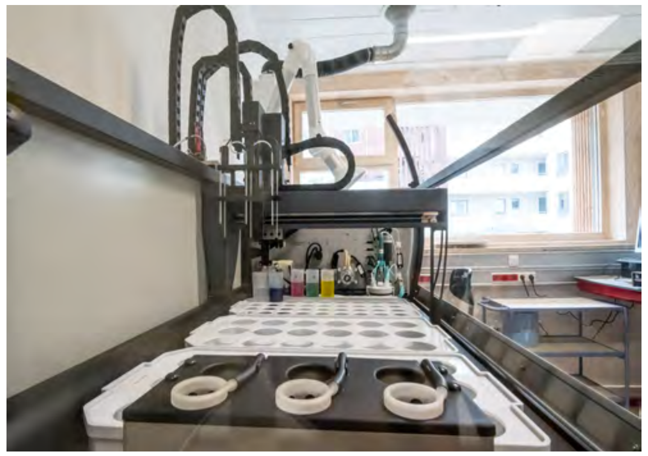
Comparison of defoliation assessment in Scots pine, Freiburg i. B., Germany, 1988. Average deviation in defoliation assessment among 10 teams from Bulgaria, the former CSSR, the former German Democratic Republic (GDR), Hungary, Poland, Spain, the former USSR, the former Yugoslavia, Italy, and the former Federal Republic of Germany (FRG).

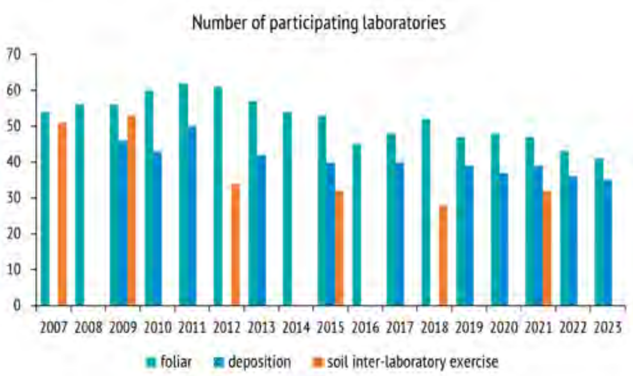


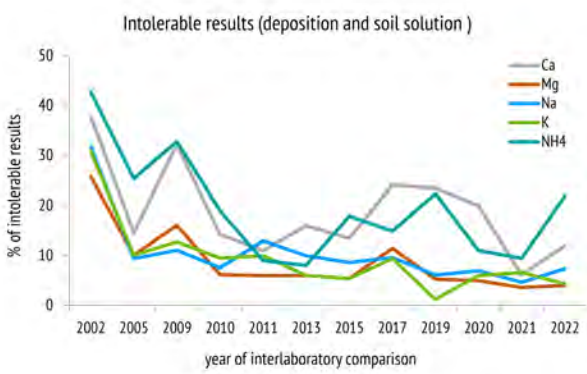
The quality of the laboratory data has distinctly improved

Anna Kowalska, Tamara Jakovljević, Michael Tatzber

Chemical analyses are an essential part of forest ecosystem monitoring. Data on nutrients and heavy metals in soil, foliage, and litterfall, as well as deposition and soil solution have been collected in the monitoring network over the past 40 years. To ensure data quality, the Quality Assurance (QA) programme has been developed.







Laboratory quality assurance

The use of reference methods and reference materials was strongly recommended for participating labs. Control charts for continuous evaluation of analytical reliability are mandatory within the program. Labs are also provided with the tools to validate and check the consistency of their data.

Inter-calibration exercises

By 2024, 26 foliage interlaboratory comparisons, 14 for deposition and soil solution, and 11 for soil had been organized with almost 100 participating laboratories. Results of the exercises are linked to the monitoring data in the database as a quality indicator. Requalification of failed laboratories aims to ensure their future compliance with the quality parameters.

Effects of interlaboratory comparisons on data quality

The quality of the data has improved distinctly over the course of the interlaboratory comparisons. The percentage of intolerable results for most parameters has fallen to less than 20% for deposition, soil solution, soil, and foliage and litterfall.

Scientific Committee: Promoting scientific evaluations and outputs

L Vesterdal, M Schaub, B De Vos, L Ukonmaanaho, A Verstraeten, N Cools, S Fleck, K Schwärzel, V Sramek, A-K Prescher, M Ferretti

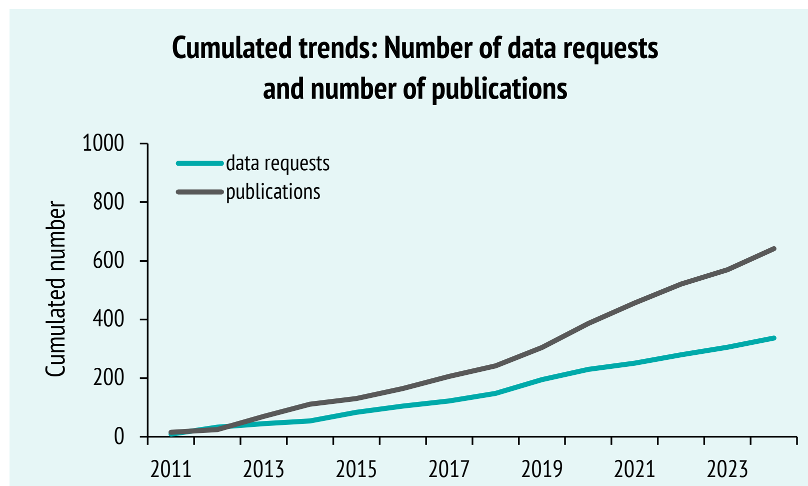
The Scientific Committee was established in 2011 with the mission to promote the scientific value of ICP Forests data, data exchange, joint publications, and conferences within ICP Forests. It is instrumental in arranging sessions at other conferences, such as IUFRO or eLTER congresses, and highlights the relevance of ICP Forests as a key infrastructure in the development of a future European forest monitoring system.

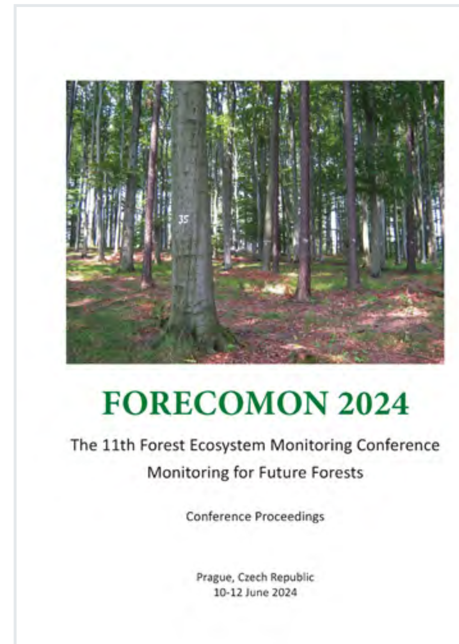
FORECOMON - Annual Scientific Conference

Since 2012, the Scientific Committee has organized the Scientific Conference of ICP Forests, now called the Forest Ecosystem Monitoring Conference FORECOMON. It is a recurring annual event with typically more than 60 contributions. FORECOMON highlights the extensive ICP Forests data series and fosters collaboration within and beyond the ICP Forests community. Novel results and conclusions from local to European scale studies are presented and discussed. Three special issues based on the conference presentations have been published in a peer-reviewed journal.

Scientific outputs increase

The number of European-wide studies based on ICP Forests data has significantly increased since 2011. Over 640 peer-reviewed papers have been published during that time through co-operation within Expert Panels and also by the wider research community following over 330 requests for ICP Forests data.





Science Stories: Beyond daily forest monitoring

The science stories in this chapter delve into scientific findings that go beyond daily monitoring. They cover topics such as tree mortality in Europe, nitrogen deposition, ectomycorrhizal fungi, and the role of forests in climate change.

PART 3

Science Stories

Science Story: Tree Mortality

Are trees in Europe's forests dying more frequently than in the past?

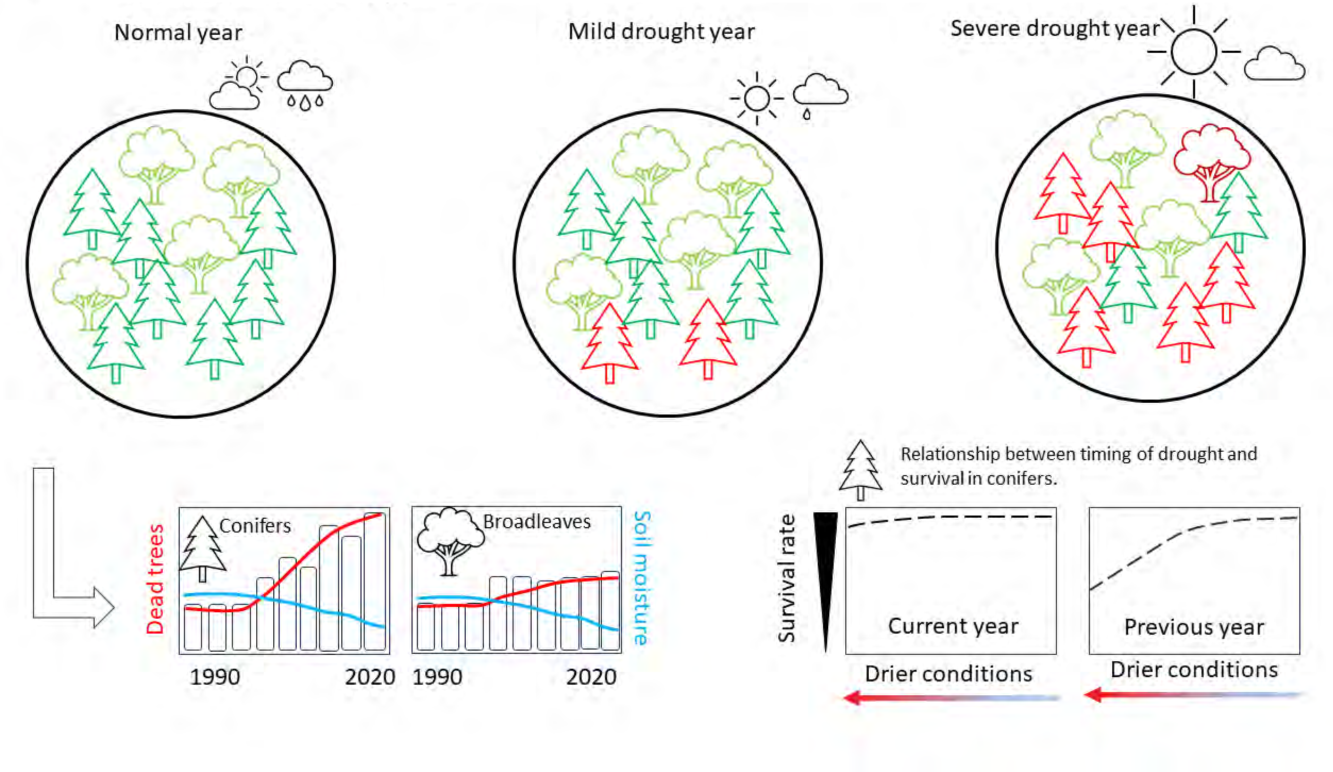
Jan-Peter George

A well-known phenomenon in these times is that we are seeing more and more dead trees in our forests. We often have the feeling that the number of trees with brown and red crown discoloration increases significantly, especially in dry years. In addition, there are reports, mostly from television and daily newspapers, in which hundreds of hectares of reddish Norway spruce trees can be seen in aerial photographs. Are these indicators of increased dieback in our forests or snapshots that are simply being disseminated in the age of audio-visual media and social networks?

ICP Forests' systematic crown condition monitoring is one of the few data sets worldwide that has been able to answer this question conclusively. With more than 3 million observations over the last decades, it has been shown that Norway spruce and Scots pine in particular react to drier growing conditions with increased dieback. Broadleaved trees such as European beech and oak, on the other hand, show a similar trend towards increased mortality in recent years, but this is much less pronounced than in conifers.

Another finding that emerged from the ICP Forests crown condition monitoring was that conifers such as Norway spruce and Scots pine often die one year after the onset of a severe drought rather than in the drought year itself. The causes of this dieback require further research, but it is likely that non-repairable damage of the wood anatomical structures together with carbon starvation leads to gradual death of the trees.

Annual observations in ICP Forests Level I plots and crown condition monitoring:
>20,000 survey plots over Europe (16 x 16 km) were analyzed and all instances of dead trees between 1987 and 2020 were counted.
Soil moisture anomaly data (blue) from the Joint Research Centre (JRC) of the European Commission were retrieved for all survey plots and is based on remote sensing data and landscape modeling.



Science Story: Nitrogen Deposition

Nitrogen deposition and forest ecosystems

Rossella Guerrieri, Nathalie Cools, Arne Verstraeten Peter Waldner, Marco Ferretti

For 40 years, ICP Forests scientists have measured the chemistry of the deposition in hundreds of monitoring plots across Europe, along with a number of variables related to soil and vegetation.

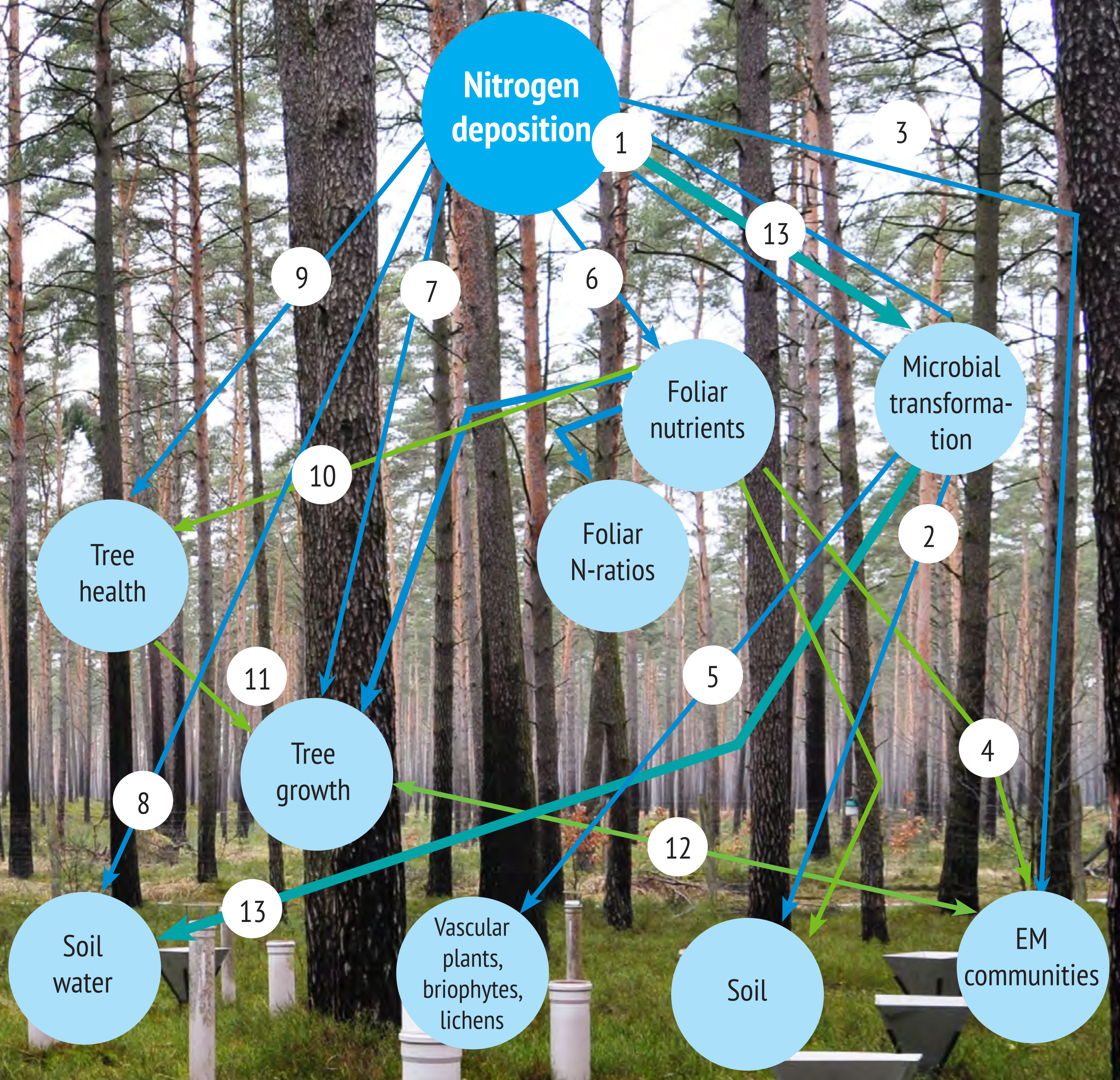
Although nitrogen (N) deposition has decreased over the past decades (1), it is still significantly affecting various components and processes that underpin forest condition and functioning. The outcomes of the investigation conducted on ICP Forests plots have allowed us to put together the complex picture of these effects, summarized in three key messages.

Firstly, N deposition has altered forest ecosystem chemistry, via direct atmospheric N input to soil (2) and soil solution (8), which is then reflected in imbalances in foliage N and other nutrient concentrations (6), or indirectly, mediated by microbial transformations in forest canopies (13) and soil (2).

Secondly, effects of N deposition on tree health (9), productivity (7), and consequently carbon sequestration have been observed across ICP Forests plots, though beneficial effects on tree growth can also occur at low to moderate deposition levels.

Lastly, besides trees, atmospheric deposition has also contributed to affecting other components of forest biodiversity, including vascular plants, mosses, and lichens (5) as well as ectomycorrhizal communities and bacteria in the soil and tree canopies (2, 13), with implications for nutrient availability (4) and tree-fungi interactions (12).

Most of the observed effects were interrelated, pointing out how pervasive, subtle, and far reaching the effect of air pollution can be.



Overview of the effects of N deposition on forest ecosystems and scientific references specifically addressing them at the ICP Forests sites. 1: Waldner et al., 2014. Atmospheric Environment 95:363-374; Schmitz et al., 2019. Environmental Pollution 244:980-994; Marchetto et al., 2021. Frontiers in Environmental Science 9:734556 (17 pp.); **2**: Vanguelova et al., 2010 Environmental Pollution 158:1857-1869; Cools et al., 2014. Forest Ecology and Management 311:3-16; **3**: van der Linde et al., 2018. Nature 561(7724):E42; **4**: Suz et al., 2021. New Phytologist 231 (5):1700-1707; **5**: van Dobben & de Vries 2017. Ecol Evol 7(1):214-227; Weldon et al., 2022. Annals of Forest Science 79:24; Salemaa et al., 2020 Environmental Pollution 261:114054; Giordani et al., 2014. Forest Ecology and Management 311:29-40 **6**: Jonard et al., 2015. Global Change Biology 21:418-4307; Ferretti et al., 2014. Global Change Biology 20 (11):3423-3438 ; Talkner et al., 2015. Annals of Forest Science 7: 919-928 **7**: Etzold et al., 2020. Forest Ecology and Management 458: 117662; **8**: Waldner et al., 2015. Annals of Forest Science 72:929-939; lost et al., 2012. Water, Air & Soil Pollution 4:1467-1479; Johnson et al., 2018. Global Change Biology 24:3606-3619; **9**: Ferretti et al., 2015. Annals of Forest Science 72:897-906; De Marco et al., 2014. Environmental Pollution 194:171-180; **10**: Veresoglou et al., 2014. New Phytologist 202:422-430; Toigo et al., 2020. Forest Ecology and Management 477, 118476 **11**: Ferreti et al., 2021. Ecological Indicators 127:107749 (14 p.); **12**: Anthony et al., 2022. ISME J 16, 1327-1336; 13: Guerrieri et al., 2024. Nat Geosci 17:130-136.

Science Story: Ectomycorrhizal Fungi

Ectomycorrhizal fungi in European forest ecosystems

Mark A. Anthony

Ectomycorrhizal fungi are among the most wide-spread fungal mutualists of European forest trees. Most growth-limiting nutrients of trees are not taken up by roots alone but via ectomycorrhizal fungal symbionts.

The ICP Forests program has enabled researchers to identify drivers of ectomycorrhizal fungal communities and their links to forest functioning. A first-of-its-kind fungal survey identified the main driver of variation in ectomycorrhizal fungal communities as the host plant species (van der Linde et al., 2018). It was later shown that ectomycorrhizal fungal species possess unique thresholds to changes in forest nutrient imbalances likely caused by nitrogen deposition (Suz et al., 2021).

More recent work on ectomycorrhizal fungal communities has focused on their effects on forest functioning. This research shows that differences in ectomycorrhizal fungal composition are linked to a three-fold variation in forest productivity (Anthony et al., 2022), and that ectomycorrhizal fungi are more tightly linked to total forest carbon storage than bacteria and other fungal groups typically found in forest soils (Anthony et al., 2024).

Ectomycorrhizal fungi are therefore unique bioindicators of forest carbon storage, important mediators of forest ecosystem functioning, and their biodiversity requires specific attention and monitoring.

Diagram showing links between ectomycorrhizal fungal community variation and forest tree growth and nutrition. © Michael Dandley www.michaeldandley.com

Science Story: Beyond Greenness

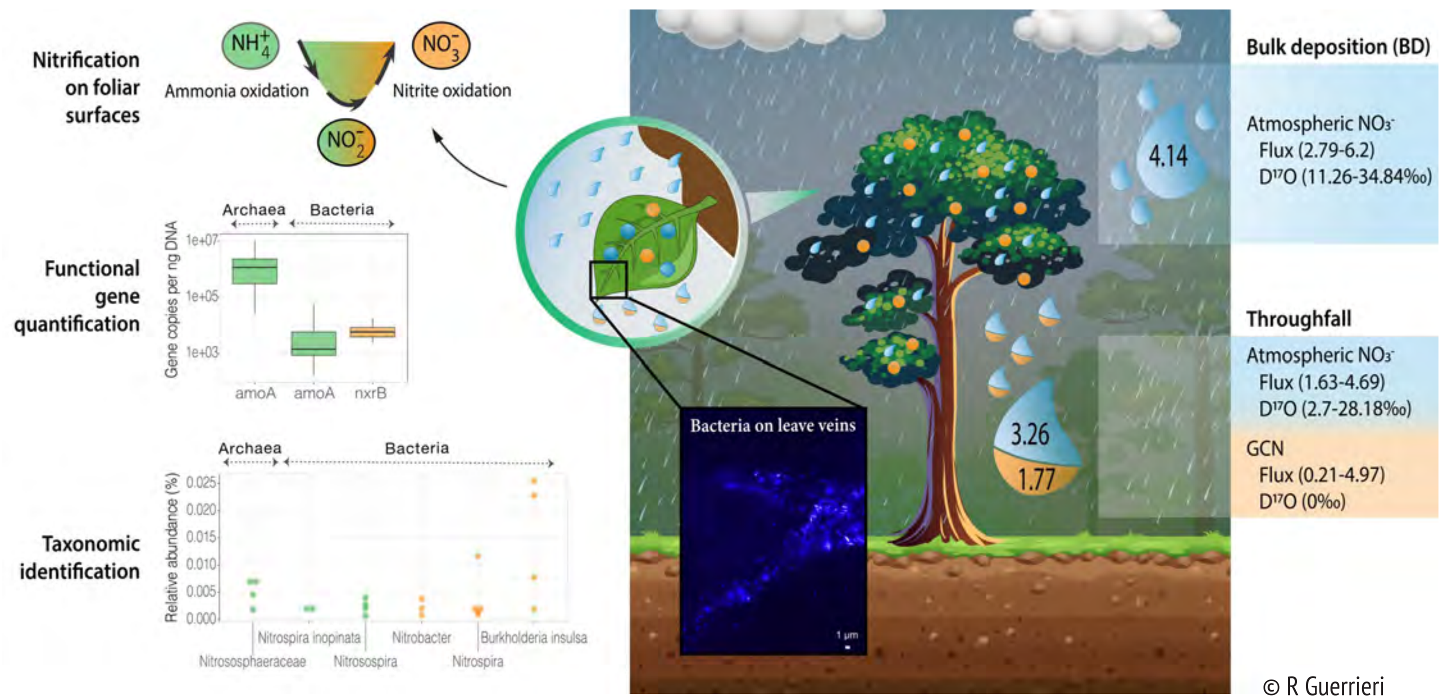
Evidence of microbial transformations occurring in tree canopies

Rossella Guerrieri, Joan Cáliz, Stefania Mattana, David Elustondo, Sofie Hellsten, Giorgio Matteucci, Päivi Merilä, Manuel Nicolas, Anne Thimonier, Elena Vanguelova, Arne Verstraeten, Peter Waldner, Emilio O. Casamayor, Josep Peñuelas, Maurizio Mencuccini

Forests significantly contribute globally to mitigating climate change by removing – through photosynthesis – around 30% of the CO_2 emitted by anthropogenic activities. This is a familiar story. What is less well known is that tree canopies (phyllosphere) and microbes inhabiting them actively interact with other compounds in the atmosphere, including reactive nitrogen (N).

Comparisons of throughfall and bulk deposition on 10 ICP Forests plots have shown that N deposition is substantially altered when interacting with forest canopies. N retention and uptake, or the washing off of dry N during precipitation events, have been proposed as the main mechanisms to explain these differences.

By combining, for the first time, N fluxes, oxygen isotope tracers in nitrate, and environmental DNA analyses, we demonstrated the occurrence of canopy nitrification (CN) in the phyllosphere of European beech and Scots pine forests. We estimated that the biological transformation of NH_4^+ to NO_3^- via CN added 0.40–4.97 kg N ha^{-1} yr^{-1} (beech) and 0.21-3.23 kg N ha^{-1} yr^{-1} (pine) to the NO_3^- from atmospheric deposition. We also documented the presence of autotrophic nitrifiers in the phyllosphere. Our data suggest that the ecological relevance of tree canopies in nutrient cycling will be underestimated if biological transformations by phyllospheric microbiota are neglected.



Using measured leaf N concentration from ICP Forests Level II plots to estimate leaf N at European scale

Yasmina Loozen

Nitrogen (N) is an essential nutrient for plants and contributes to tree health and functioning. It plays an important role in photosynthesis, the process through which plants grow. However, excess N invokes a series of harmful effects on forest ecosystems including reduced tree growth and enhanced susceptibility to pests and diseases. For this reason, leaf N, the concentration of nitrogen in tree leaves, is measured regularly on ICP Forests Level II plots.

While there are many ICP Forests plots throughout Europe, the ground foliar measurements only give discrete information for the sampling sites. Obtaining large-scale information about leaf N would improve our understanding of forests' N-status and nutrition, and the influence of N on tree photosynthesis.

Combining measured leaf N concentrations with remote sensing data, acquired from satellites, as well as environmental maps could help us estimate leaf N at European scale. The prediction is based on the random forests statistical model that estimates leaf N at locations where it was not sampled using remote sensing and environmental data as predictors. Leaf N data from ICP Forests plots were used to train the model.

The results showed that the leaf N estimation was more reliable for all forest types (r^2 = 0.62) or for coniferous forests alone (r^2 = 0.49), compared to deciduous forests (r^2 = 0.39). While higher leaf N concentration (1.8 - 2.6%) were predicted in the central part of Europe, lower concentration (0.8 – 1.6 %) were predicted in the southern and northern part of the continent.

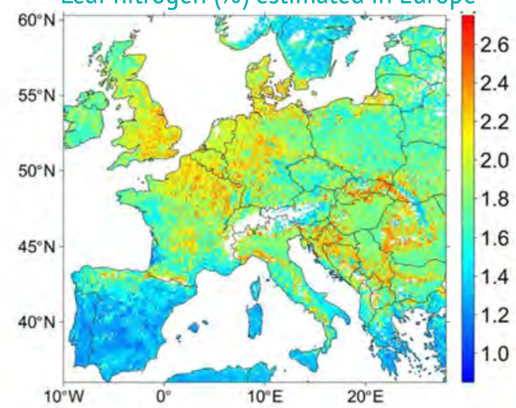
Leaf nitrogen measured at ICP Forests plots

Location of the ICP Forests plots in Europe. The colour represents the leaf N concentration (%).

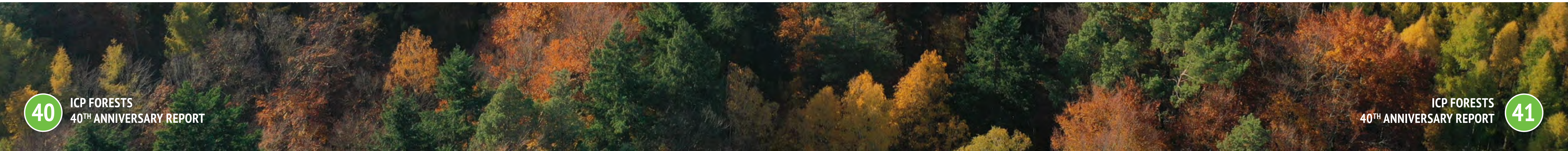
Random Forests Statistical Model

Random forests model includes numerous decision trees to estimate leaf nitrogen based on multiple remote sensing and environmental predictors.

Leaf nitrogen (%) estimated in Europe



Estimated leaf N map for all forest types, i.e. needleleaf, broadleaf and mixed forests.



PART 4

The future: ICP Forests as a multifunctional, pan-European monitoring infrastructure

ICP Forests: towards the next 40 years

M Ferretti, N Cools, B De Vos, ML Dörner, S Fleck, AK Prescher, M Schaub, K Schwärzel, V Šrámek, L Ukonmaanaho, L Vesterdal, A Verstraeten, P Waldner

Four decades after the inception of ICP Forests, monitoring is now firmly established as an essential scientific approach to inform forest policy and management, and the demand for harmonized approaches has even increased (Bontemps et al., 2021; Breidenbach et al., 2025; European Commission, 2023; Ferretti, 2021; Ferretti et al., 2024b; ITMN, Senf et al., 2025). Confronted with evolving priorities and challenging political, environmental and societal conditions, ICP Forests should now envision its future. There are several authors providing suggestions on do's and don'ts of monitoring programs (e.g. Legg and Nagy, 2006; Lindenmayer and Likens, 2009; Lovett et al., 2007; Parr et al., 2001; Percy and Ferretti, 2004; Spellerberg, 1994; Vos et al., 2011). Here, however, we intent offering a broader framework for a long-term perspective based on what we have learned after 40 years of international co-operative forest monitoring.

Five important lessons

Lesson 1: Forests are complex ecosystems; their condition and dynamics are driven by several factors whose effects vary in time, space, and intensity. To capture this complexity, monitoring needs to be comprehensive (portfolio of measurements), reliable (statistically sound, quality assured), flexible (to adapt), reactive, and proactive. The latter involves actively observing and detecting effects before they escalate into significant challenges.

Lesson 2: Priorities (scientific, political) have changed and will continue to change. The history of ICP Forests demonstrates how scientific and political priorities can evolve. The monitoring design of ICP Forests was able to accommodate new priorities (e.g. loss of biodiversity and climate change). Priorities, however, will continue to evolve, and ICP Forests needs to stay tuned to address future grand challenges.

Lesson 3: Technological evolution opens perspectives. Since ICP Forests was launched, technology has progressed at an unprecedented pace in all fields (e.g. close-range and remote sensing tools, x-omics, computational power, modeling, ...). This development can pave the way for optimizing and enhancing forest monitoring (e.g. Ferretti et al., 2024a) and needs to be taken into account in future activities.

Lesson 4: Ground-based monitoring remains essential. Complexity, changing priorities, and rapid technological evolution render ground-based monitoring programs even more crucial for (i) covering specific measurement needs and targets (e.g. forest health diagnosis, mycorrhiza, soil properties, below-canopy processes) otherwise difficult to satisfy and/or reach; (ii) understanding ecosystem properties and ecological processes; (iii) providing harmonized and comparable platforms for evolving measurement targets, approaches and techniques; and (iv) validating remotely sensed data and model outputs.

Lesson 5: ICP Forests remains a valid model for international forest monitoring, but needs support. At a time when changes in forest condition are often triggered by factors (e.g. those related to climate change) that are of regional to global nature and effects, ICP Forests' pioneering experience with transboundary air pollution is of outstanding value. ICP Forests was conceived in view of its international dimension, and monitoring design, expertise and governance has proven robust and effective over four decades. The international framework within the UNECE Air Convention, the long-term co-operation with the European Commission and the continuous support (political and institutional, financial, scientific, and technical) from various actors at national and international levels were essential to ICP Forests, and should be strengthened in the future.

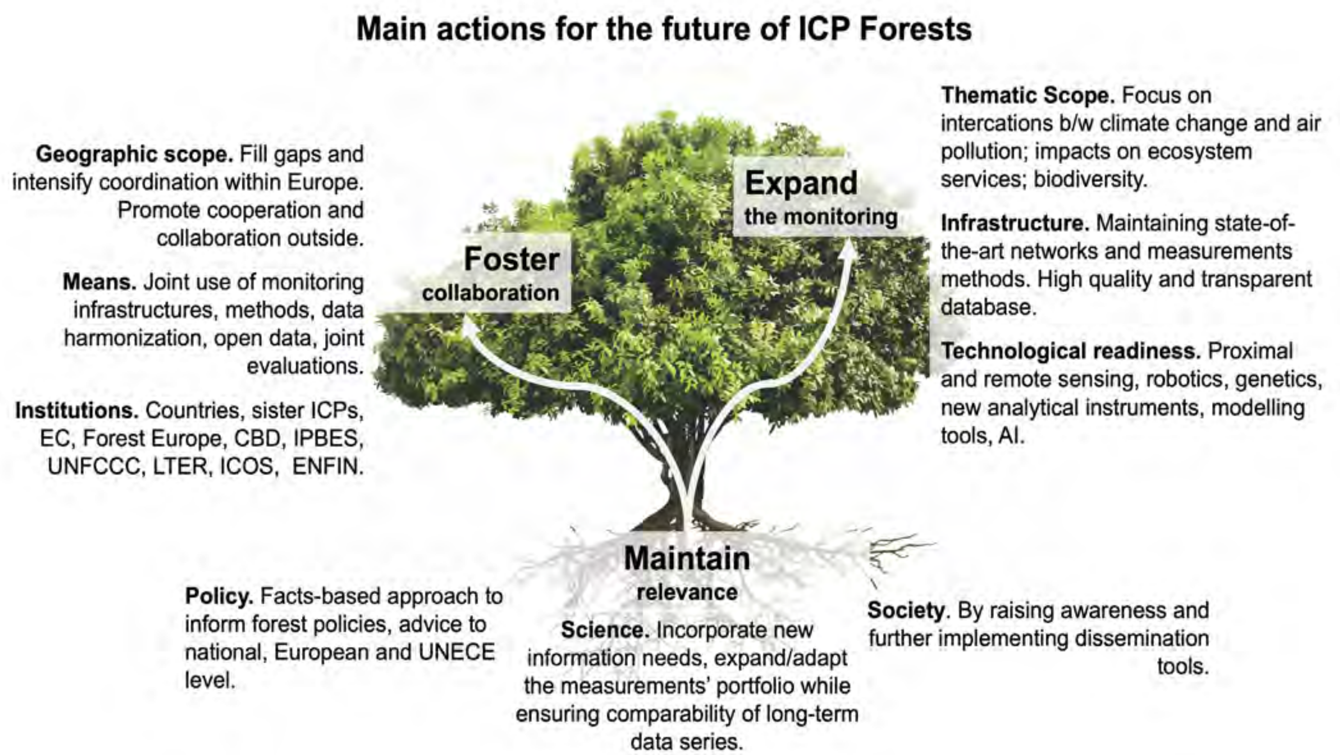
Towards the next 40 years

It is impossible to foresee what will happen in the next decades. Rather, it is feasible to identify key actions that will support the development of ICP Forests over a large range of possible scenarios. Besides the lessons learned, these actions are grounded on a firm belief: ICP Forests will continue advocating for a sustainable, co-operative, internationally harmonized forest monitoring system to respond to global challenges. ICP Forests' strategy for the future can consider including three main categories of actions.

Maintain. Staying relevant at political, scientific and societal levels is indispensable to secure support for monitoring activities and represent a permanent long-term goal of ICP Forests. It implies being able to provide state-of-the-art answers to policy, science, and society. In this context, securing ICP Forests' relevance within the scope of the Working Group of Effects of the UNECE Air Convention is a priority.

Foster. Fostering collaboration remains key to addressing gaps in the European coverage and to expanding harmonized monitoring in other parts of the UNECE region and beyond. This can be achieved by fostering co-ordination with institutions at national and European level, and through the joint use of infrastructures, methods, and data.

Expand. Expanding the monitoring needs (i) broadening the thematic scope and (ii) updating the monitoring infrastructures to maintain technological readiness and the ability to address new information requirements. Further developing ICP Forests' themes (e.g. climate change and its interactions with air pollution), methods (e.g. continuous updating an expanded portfolio of measurements), technology (e.g. proximal and remote sensing, robotics, genetics, modelling, AI-related tools) and FAIRness of its data and data products should be a continuous activity.



Main actions for the future development of ICP Forests. Fostering collaboration and expanding monitoring activities are rooted in the ability to maintain relevance at political, scientific, and societal level (© M Ferretti).

APPENDIX

Acknowledgements

The past 40 years have been characterized by an unprecedented, still unrivaled sharing of expertise across national borders to achieve common goals to better monitor our forests. The Chairman and the Programme Co-ordinating Centre of ICP Forests would like to thank all those who contributed to the success of the program.

We are grateful to the Secretariat of the UNECE Air Convention for the continuous support, and to the European Commission for the co-operation and support over many years. The participating countries were the main pillars of the program: With their current and past delegates, National Focal Centers, experts, and co-operating institutions, their dedicated work ensured the continuous operation of our monitoring networks and the basic expertise needed for the progress of the program.

The Expert Panels, Groups and Committees worked intensively and over decades to identify, compile, compare, and harmonize monitoring methods, ensuring quality assured data and sound evaluations. All co-operating scientists, experts, and organizations (e.g. Forest Europe, EANET) that made use of our data and methods to investigate trends, patterns and processes undergoing in European forests or contributed to advance our methods.

We hope that such a fertile co-operation environment will continue and even expand in the future – we will work for it. We look forward to many more years of international co-operation.

Joint Expert Panel Meeting 2019, Brussels

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Cover TI-WO/Öko; Vecteezy.com | 4-5 K Clemens, Thünen | 7 ML Dörner, Thünen | 8 A Fürst, BFW; J Kaplick, LFE; Lehmann; G Schnabel, BFW; M Vejpustková, VÚLHM; E Vanguelova, Forest Research | 9 T Schindler | 11 INBO; NFC Estonia | 12-13 Vecteezy.com | 15 A Michel, Thünen | 16-17 Vecteezy.com | 18 F Mittermeier, Pexels.com | 19 T Bender, HNEE | 20 L Hamberg, LUKE; F Máliš, TU Zvolen; A Michel, Thünen | 21 Lehmann | 22 ML Dörner, Thünen | 23 V Fadrhonsová, VÚLHM | 24 E Vanguelova, Forest Research | 25 V Fadrhonsová , VÚLHM | 26 NFC Estonia | 28 E Dimitrov, eLTER; D Evgeni, eLTER | 30-31 K Clemens, Thünen | 32-33 A Michel, Thünen | 34-35 TGM Sanders, Thünen | 36-37 L Martinez-Suz, Kew | 38-39 R Canullo, UNICAM | 40-41 K Clemens, Thünen | 42 ML Dörner, Thünen | 43 D Evgeni, eLTER; E Oksanen, LUKE | 45 ML Dörner, Thünen | 46 INBO | 48 L Kutnar, SFI | 61 NFC Latvia

References and further readings

Statement by Marco Ferretti, Chair of ICP Forests (p. 5)

Forest Europe (2020) State of Europe's Forests. Publisher: Ministerial Conference on the Protection of Forests in Europe. https://foresteurope.org/wp-content/uploads/2016/08/SoEF_2020.pdf

Lovett GM, Burns DA, Driscoll CT, et al. (2007) Who needs environmental monitoring? Front Ecol Environ 5(5):253–260. https://doi.org/10.1890/1540-9295(2007)5[253:WNEM]2.0.CO;2

Introduction: The Air Convention's journey in combating transboundary pollution (p. 7)

UNECE (2025) Global experts chart path forward on cooperation for transboundary air pollution. https://unece.org/media/environment/Air-Pollution-Convention/news/401016

ICP Forests across 40 years of changes (p. 9)

Breidenbach J, Bastrup-Birk A, Ferretti M, et al. (2024) A Governance Structure for a European Forest Monitoring System. PathFinder Policy Brief 1, 12/2024. https://pathfinder-heu.eu/resources

EEC (1986) Council Regulation (EEC) No 3528/86 of 17 Nov 1986 on the Protection of the Community's forests against atmospheric pollution. Official Journal of the European Communities No L 326/2 of 21.11.1986:2–4. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex:31986R3528 (access date: 10/01/2024)

European Commission (2023a) Proposal for a regulation of the European Parliament and of the Council on a monitoring framework for resilient European forests. Brussels, 22.11.2023, COM (2023) 728 final, 2023/0413 (COD): 25 p. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2023:728:FIN

Ferretti M (2021) New appetite for the monitoring of European forests. Ann For Sci 78(4), 94 (4 p). https://doi.org/10.1007/s13595-021-01112-w

Ferretti M, Gessler A, Cools N, et al. (2024) Resilient forests need joint forces for better inventorying and monitoring. For Ecol Manage 561, 121875. https://doi.org/10.1016/j.foreco.2024.121875

Ferretti M, Fischer R (eds) (2013) Forest Monitoring: Methods for terrestrial investigations in Europe with an overview of North America and Asia. Developments in Environmental Science, Vol. 12. Elsevier. ISBN: 9780080982229

Ferretti M, König N, Rautio P, Sase H (2009) Quality assurance (QA) in international forest monitoring programmes: Activity, problems and perspectives from East Asia and Europe. Ann For Sci 66(4): 1–12. https://doi.org/10.1051/forest/2009025

ICP Forests (2022) Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests. Thünen Institute of Forest Ecosystems, Eberswalde Germany. http://icp-forests.net/page/icp-forests-manual

Kandler O, Innes JL (1995) Air pollution and forest decline in Central Europe. Environ Pollut 90(2):171–180. https://doi.org/10.1016/0269-7491(95)00006-D

Schwärzel K, Seidling W, Hansen K, et al. (2022) Part I: Objectives, strategy and ilmplementation of ICP Forests. Version 2022-2. In: UNECE ICP Forests Programme Co-ordinating Centre (ed.): Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests. Thünen Institute of Forest Ecosystems, Eberswalde, Germany, 12 p + Annex

Schütt P, Cowling EB (1985) Waldsterben, a general decline of forests in central Europe: symptoms, development and possible causes. Plant Dis 69:548. https://doi.org/10.1094/PD-69-548.

Skelly JM, Innes J L (1994) Waldsterben in the forests of central Europe and Eastern North America: fantasy or reality? Plant Dis 78(11):1021–1032. https://doi.org/10.1094/PD-78-1021

Wellbrock N, Cools N, De Vos B, et al. (2024) There is a need to better take into account forest soils in the planned soil monitoring law of the European Union. Ann For Sci 81, 22. https://doi.org/10.1186/s13595-024-01238-7

Forest growth across Europe is affected by multiple factors. A perspective from tree to ecosystem level (p. 19)

Anthony MA, Crowther TC, van der Linde S, et al. (2022) Forest tree growth is linked to mycorrhizal fungal composition and function across Europe. ISME J 16:1327–1336. https://doi.org/10.1038/s41396-021-01159-7

De Wergifosse L, André F, Goosse H, et al. (2022). Simulating tree growth response to climate change in structurally diverse oak and beech forests. Sci Total Environ 806, 150422. https://doi.org/10.1016/j.scitotenv.2021.150422

Etzold S, Ferretti M, Reinds GJ, et al. (2020) Nitrogen deposition is the most important environmental driver of growth of pure, even-aged, and managed European forests. For Ecol Manage 458:117762. https://doi.org/10.1016/j.foreco.2019.117762

Nussbaumer A, Gessler A, Benham S, et al. (2021) Contrasting resource dynamics in mast years for European beech and oak – a continental scale analysis. Front For Glob Change 4. https://doi.org/10.3389/ffgc.2021.689836

Biodiversity and ground vegetation in Europe are affected by N deposition and climate change (p. 20)

Antão LH, Weigel B, Strona G, et al. (2022) Climate change reshuffles northern species within their niches. Nat Clim Chang 12:587–592. https://doi.org/10.1038/s41558-022-01381-x

Dirnböck T, Grandin U, Bernhardt-Römermann M, et al. (2014) Forest floor vegetation response to nitrogen deposition in Europe. Global Change Biol 20(2):429-440. https://doi.org/10.1111/gcb.12440

Seidling W, Hamberg L, Máliš F, et al. (2020) Comparing observer performance in vegetation records by efficiency graphs derived from rarefaction curves. Ecol Indic 109:105790. https://doi.org/10.1016/j.ecolind.2019.105790

Weldon J, Merder J, Ferretti M, Grandin U (2022) Nitrogen deposition causes eutrophication in bryophyte communities in central and northern European forests. Ann For Sci 79:24. https://doi.org/10.1186/s13595-022-01148-6

Ambient air pollution is still affecting European forests (p. 22)

Ferretti M, Cailleret M, Haeni M, et al. (2024) The fingerprint of tropospheric ozone on broadleaved forest vegetation in Europe. Ecol Indic 158, 111486. https://doi.org/10.1016/j.ecolind.2023.111486

Pitar D, Hůnova I, Gottardini E, et al. (2023) Air quality in European forests - Nitrogen compounds trends in the ICP Forests Level II network. Forest science for people and societal challenges – The 90th „Marin Drăcea" INCDS Anniversary Conference, 2–5 Oct 2023, Bucharest, Romania

Forest soil between air pollution and climate change (p. 24)

Ballabio C, Jones A, Panagos P (2024) Cadmium in topsoils of the European Union – an analysis based on LUCAS topsoil database. Sci Total Environ 912, 168710. https://doi.org/10.1016/j.scitotenv.2023.168710

Tree foliage and litterfall reveal declining tree nutritional status and improve the assessment of carbon dynamics (p. 26)

Braun S, Schindler C, Rihm B (2020) Foliar nutrient concentrations of European beech in Switzerland: Relations with nitrogen deposition, Ozone, climate and soil chemistry. Frontiers in Forests and Global Change 3. https://doi.org/10.3389/ffgc.2020.00033

Du E, van Doorn M, de Vries W (2021) Spatially divergent trends of nitrogen versus phosphorus limitation across European forests. Sci Total Environ 771:145391. https://doi.org/10.1016/j.scitotenv.2021.145391

Jonard M, Fürst A, Verstraeten A, et al. (2015) Tree mineral nutrition is deteriorating in Europe. Global Change Biol 21:418–430. https://doi.org/10.1111/gcb.12657

Neumann M, Ukonmaanaho L, Johnson J, et al. (2018) Quantifying carbon and nutrient input from litterfall in European forests using field observations and modeling. Global Biogeochem Cy 32:784–798. https://doi.org/10.1029/2017GB005825

Nussbaumer A, Gessler A, Benham S, et al. (2021) Contrasting resource dynamics in mast years for European beech and oak — a continental scale analysis. Frontiers in Forests and Global Change 4. https://doi.org/10.3389/ffgc.2021.689836

Peñuelas J, Fernández-Martínez M, Vallicrosa H, et al. (2020) Increasing atmospheric CO2 concentrations correlate with declining nutritional status of European forests. Commun Biol 3:1–11. https://doi.org/10.1038/s42003-020-0839-y

Talkner U, Meiwes KJ, Potočić N, et al. (2015) Phosphorus nutrition of beech (*Fagus sylvatica* L.) is decreasing in Europe. Ann For Sci 72:919–928. https://doi.org/10.1007/s13595-015-0459-8

An overall Quality Assurance perspective for ICP Forests (p. 27)

Ferretti M, König N, Granke O, Nicolas M (2021) Part III: Quality Assurance within the ICP Forests monitoring programme. Version 2021-1. In: UNECE ICP Forests Programme Co-ordinating Centre (ed.): Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests. Thünen Institute of Forest Ecosystems, Eberswalde, Germany, 14 p + Annex

Ferretti M, Fischer R, Mues V, et al. (2020) Part II: Basic design principles for the ICP Forests Monitoring Networks. Version 2020-2. In: UNECE ICP Forests Programme Co-ordinating Centre (ed.): Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests. Thünen Institute of Forest Ecosystems, Eberswalde, Germany, 33 p + Annex

The quality of the laboratory data has distinctly improved (p. 28)

Fürst A, Kowalska A, Brunialti G, et al. (2020) Part XVI: Quality Assurance and Control in Laboratories. Version 2020-1. In: UNECE, ICP Forests Programme Co-ordinating Centre (ed.): Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests. Thünen Institute of Forest Ecosystems, Eberswalde, Germany, 46 p + Annex

Part 4. ICP Forests: towards the next 40 years (p. 43)

Bontemps JD, Bouriaud O, Vega C, et al. (2022) Offering the appetite for the monitoring of European forests a diversified diet. Ann For Sci 79, 19. https://doi.org/10.1186/s13595-022-01139-7

Breidenbach J, Bastrup-Birk A, Ferretti M, et al. (2025) A governance structure for a European forest monitoring system. A federated system with a centralized component. PathFinder Policy Brief 1. https://doi.org/10.5281/zenodo.14391893

European Commission (2023) Proposal for a regulation of the European Parliament and of the Council on a monitoring framework for resilient European forests. Brussels, 22.11.2023, COM (2023) 728 final, 2023/0413 (COD). 25 p. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2023:728:FIN

Ferretti M, Fischer C, Gessler A, et al. (2024a) Advancing forest inventorying and monitoring. Ann For Sci 81(1):6. https://doi.org/10.1186/s13595-023-01220-9

Ferretti M, Gessler A, Cools N, et al. (2024b) Perspectives: Resilient forests need joint forces for better inventorying and monitoring. Forest Ecol Manage 561. https://doi.org/10.1016/j.foreco.2024.121875

Ferretti M (2021) New appetite for the monitoring of European forests. Ann For Sci 78(4): 94 (4 p). https://doi.org/10.1007/s13595-021-01112-w

ITMN, Senf C, Esquivel Muelbert A, Pugh T, et al. (2025) Towards a global understanding of tree mortality. New Phytol 245:2377–2392. https://doi.org/10.1111/nph.20407

Legg C, Nagy L (2006) Why most conservation monitoring is, but need not be, a waste of time. J Environ Manage 78:194–199. https://doi.org/10.1016/j.jenvman.2005.04.016

Lindenmayer DB, Likens GE (2009) Adaptive monitoring: a new paradigm for long-term research and monitoring. Trends Ecol Evol 24(9):482–486. https://doi.org/10.1016/j.tree.2009.03.005

Lovett GM, Burns DA, Driscoll CT, et al. (2007) Who needs environmental monitoring? Front Ecol Environ 5(5):253–260. https://doi.org/10.1890/1540-9295(2007)5[253:WNEM]2.0.CO;2

Parr TW, Ferretti M, Simpson IC, et al. (2002) Towards a long-term integrated monitoring programme in Europe: network design in theory and practice. Environ Monit Assess 78(3):253–290. https://doi.org/10.1023/A:1019934919140

Percy KE, Ferretti M (2004) Air pollution and forest health: towards new monitoring concepts. Environ Pollut 130:113–126. https://doi.org/10.1016/j.envpol.2003.10.034

Spellerberg IF (1994) Monitoring Ecological Change. Cambridge University Press, Cambridge, UK. https://doi.org/10.1017/CBO9780511614699

Vos P, Meelis E, Ter Keurs WJ (2000) A framework for the design of ecological monitoring programs as a tool for environmental and nature management. Environ Monit Assess 61:317–344

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Working Group on Effects WGE
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https://www.emep.int/

ICP Integrated Monitoring
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ICP Vegetation
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Co-operation with other international organizations

Acid Deposition Monitoring Network in East Asia EANET
https://www.eanet.asia/

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