United Nations ECE/EB.AIR/GE.1/2022/11–ECE/EB.AIR/WG.1/2022/4

Economic and Social Council

Distr.: General
25 August 2022

English only

Economic Commission for Europe

Executive Body for the Convention on Long-range Transboundary Air Pollution

Steering Body to the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe

Working Group on Effects

Eighth joint session
Geneva, 12–16 September 2022
Item 2 (c) (ii) of the provisional agenda
Progress in activities in 2022 and further development of effects-oriented activities: air pollution effects on materials, the environment and crops: air pollution effects on forests

Effects of air pollution on forests[*]

Progress report by the Programme Coordinating Centre of the International Cooperative Programme on Assessment and Monitoring of Air Pollution Effects on Forests

Summary

The present report by the Programme Coordinating Centre of the International Cooperative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) describes the outcomes of activities carried out since the previous report (ECE/EB.AIR/GE.1/2021/11–ECE/EB.AIR/WG.1/2021/4) and presents the outcomes of the thirty-eighth meeting of the ICP Forests Task Force (online), 2 and 3 June 2022). The activities were carried out in accordance with the 2022–2023 workplan for the implementation of the Convention on Long-range Transboundary Air Pollution (ECE/EB.AIR/148/Add.1, table 1, item 1.1.1.17) and in accordance with the revised mandate for the International Cooperative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (Executive Body decision 2019/16).[a]

Based on the analysis of 277 ICP Forests level II and Swedish Throughfall Monitoring Network plots across Europe in 2020, regional patterns in throughfall deposition were identified. High values of nitrate deposition were mainly found in Central and Western Europe (eastern Austria, Belgium, Czechia, Denmark, Germany and Switzerland), while for ammonium they were also found in northern Italy and Poland. It is generally considered that negative effects of nitrogen deposition (i.e. the sum of nitrate and ammonium deposition) on forests become evident when inorganic nitrogen deposition is higher than a specific threshold, known as the critical load. The empirical critical load[b] for deciduous forests is 10 – 20 kg N ha^{-1} y^{-1} and 5 - 15 kg N ha^{-1} y^{-1} for coniferous forests. The 2020 throughfall inorganic nitrogen (N) deposition measurements indicate that critical loads are currently

[*] The present document is being issued without formal editing.

exceeded at many forest sites in Europe; N deposition higher than 10 kg ha-1 y-1 were mainly measured in Central and Western Europe including Austria, Belgium, Czechia, Germany, northern Italy and Switzerland.

The 2021 transnational crown condition survey was conducted on 106,451 trees on 5,565 plots in 27 countries. The overall mean defoliation for all species was 23.3 per cent: there was no change for broadleaved and a very slight increase in defoliation for conifers trees in comparison with 2020. Broadleaved trees showed a higher mean defoliation than coniferous trees (23.3 per cent versus 22.4 per cent, respectively). The damage assessment revealed that insects were again the predominant biotic cause of damage, being responsible for 24.6 per cent of all recorded damage symptoms, while abiotic agents were the second major causal agent group, being responsible for 16.2 per cent of all damage symptoms. Drought was the most reported abiotic agent causing damage.

[a] Available at www.unece.org/env/lrtap/executivebody/eb_decision.html.

[b] Roland Bobbink and Jean-Paul Hettelingh, eds., *Review and revision of empirical critical loads and dose-response relationships: Proceedings of an expert workshop, Noordwijkerhout (Netherlands), 23–25 June 2010* (Coordination Centre for Effects/National Institute for Public Health and the Environment of the Netherlands, 2011).

I. Introduction

1. The present report of the International Cooperative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) is submitted for consideration by the Working Group on Effects in accordance with the 2022–2023 workplan for the implementation of the Convention on Long-range Transboundary Air Pollution (ECE/EB.AIR/148/Add.1, table 1, item 1.1.1.17) and in accordance with the revised mandate of ICP Forests (Executive Body decision 2019/16).[1]

2. Germany is the lead country of ICP Forests, the Programme Coordinating Centre of which is hosted by the Johann Heinrich von Thünen Institute (Federal Research Institute for Rural Areas, Forestry and Fisheries) under the Federal Ministry of Food and Agriculture. Since 2017, the Chairman of the ICP Forests' Task Force is hosted by the Swiss Federal Institute for Forest Snow and Landscape Research (WSL). A total of 42 Parties to the Convention participate in ICP Forests activities.

3. The thirty-eighth ICP Forests Task Force Meeting was held online from June 2-3, 2022. The tenth ICP Forests scientific conference "Forest dynamics in the Anthropocene – Integrated monitoring toward a whole system approach" was postponed to 2023.

II. Outcomes and deliverables during the reporting period

4. During the reporting period, ICP Forests produced or contributed to the following publications and reports:

(a) The 2021 joint progress report on contribution to the review of the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (ECE/EB.AIR/GE.1/2021/3–ECE/EB.AIR/WG.1/2021/3);

(b) The 2021 progress report by the Programme Coordinating Centre of ICP Forests to the EMEP Steering Body and the Working Group on Effects (ECE/EB.AIR/GE.1/2021/11–ECE/EB.AIR/WG.1/2021/4);

(c) The effectiveness of the Gothenburg Protocol was evaluated using monitoring results from ICP Forests as part of the Gothenburg Protocol review;

(d) The 2022 Technical Report (TR) of ICP Forests,[2] which presents results from 32 of the 42 countries participating in ICP Forests, including:

(i) A concise overview by the EP Chairs of the most relevant key findings in the scientific literature in the forest-relevant, priority themes for the WGE strategic planning: N deposition, ozone, heavy metals, air pollution/climate change interactions;

(ii) A list of 70 scientific publications for which ICP Forests data and/or the ICP Forests infrastructure were used;

(iii) A list of all 21 official requests for ICP Forests data between January and December 2021;

(iv) A review of the 9th ICP Forests Scientific Conference FORECOMON 2021.

(v) Atmospheric throughfall deposition in European forests in 2020;

(vi) Tree crown condition in 2021;

(vii) History and progress of the ICP Forests ring-test programme and the Working Group Quality Assurance (QA) and Quality Control (QC) in Laboratories.

[1] Available at www.unece.org/env/lrtap/executivebody/eb_decision.html.

[2] Alexa Michel, Till Kirchner, Anne-Katrin Prescher and Kai Schwärzel, eds., "Forest Condition in Europe: The 2022 Assessment. The ICP Forests Technical Report under the UNECE Convention on Long-range Transboundary Air Pollution" (forthcoming).

5. The results from the Working Group on QA and QC on the 24th Needle/leaf Interlaboratory Comparison Test 2021/2022 with 47 laboratories from 25 countries, the 11th Deposition and Soil Solution Working Ringtest 2021/2022 with 39 labs from 23 countries, and the 10th Soil Ringest 2021 with 32 labs from 21 countries were published[3].

6. ICP Forests contributed to the development of the Science Strategy 2022-2030 and beyond of the Air Convention.

7. In the frame of the review of the Gothenburg Protocol, ICP Forests developed two factsheets for the informal document and contributed to the two official documents.

8. ICP Forests Brief No. 5 “Tree health is deteriorating in the European Forests”[4] was published.

9. ICP Forests, together with the Federal Office for the Environment (Switzerland) and the Northwest German Forest Research Institute, organized a special forest session at the 8th Global Nitrogen Conference. At this session, the work of ICP Forests related to the effects of nitrogen deposition on forest ecosystems was presented and discussed. The conference was held online from 30 May to 3 June 2021.

10. ICP Forests and Forest Europe co-hosted a policy event entitled Monitoring and Assessing Forest Health on the International Day of Forest (March 21, 2022). This webinar addressed the policy perspective of forest health monitoring, current criteria and indicators, and future needs for decision making. At the same time, recent developments in the field of forest environmental monitoring were presented. Then, a case study was used to demonstrate how forest environmental monitoring has contributed to policy development. Finally, a panel discussion addressed common challenges and opportunities, in particular how to improve information transfer between policy, science and practice.

III. Expected outcomes and deliverables for the next reporting period and in the longer term

11. In the second half of 2022 and in 2023, ICP Forests will carry out the following activities, in accordance with the 2022–2023 workplans for the Convention and with the decisions taken at the thirty-eighth meeting of the Task Force:

(a) Further acquisition of data on the condition and development of forest ecosystems and efforts to improve data quality and the data management system;

(b) Contribution to the 2022 Scientific information for the review of the Gothenburg Protocol (ECE/EB.AIR/GE.1/2022/3–ECE/EB.AIR/WG.1/2022/3);

(c) Finalization of the draft 2022 Technical Report of ICP Forests;

(d) Publication of ICP Forests Brief No. 6: Evidence of links between air pollution, changes in ectomycorrhizal fungi composition and nutritional imbalances in Europe's forests;

(e) Preparing for publication of ICP Forests Brief No. 7, which addresses heavy metal deposition in topsoils of ICP Forests Level I plots.

IV. Cooperation with other groups, task forces and subsidiary bodies, including with regard to synergies and possible joint activities

12. ICP Forests participated in the Expert Workshop on Empirical Critical Loads for Nitrogen (26 - 28 Oct 2021, Berne, Switzerland) organised by ICP Modelling & Mapping. ICP Forests contributed to the review and revision of the empirical critical load for nitrogen (CLempN) as author and reviewer of the book chapters.

[3] http://icp-forests.net/page/working-group-on-quality.
[4] Nenad Potočić and others (Eberswalde, Germany, Thünen Institute of Forest Ecosystems, 2021).

V. Strengthening the involvement of countries of Eastern and South-Eastern Europe, the Caucasus and Central Asia

13. Most of the countries of South-Eastern Europe, as well as Türkiye, are included in the extensive ICP Forests Level I monitoring of forest ecosystems. The more complex and intensive Level II monitoring is carried out at only a few sites in South-Eastern Europe. None of the countries of the Caucasus or Central Asia is active in ICP Forests monitoring activities. ICP Forests takes every opportunity – for example, at ICP Forests scientific conferences – to contact these countries.

VI. Scientific and technical cooperation with relevant international bodies

14. ICP Forests participated in the National Emissions Ceiling Ecosystems Expert Group meeting (online, 24 June 2021 and 28 October 2021), organized by the Clean Air Unit (Directorate General of the Environment) of the European Commission.

15. ICP Forests participates regularly in the National Reference Centres/European Environment Information and Observation Network Forests webinars organized by the European Environment Agency. These webinars present and discuss items related to the development of the Forest Information System for Europe to support policies aimed at the protection and sustainable and multifunctional use of forests in Europe.

16. In 2021, ICP Forests participated in the task force meetings of the International Cooperative Programme on Integrated Monitoring of Air Pollution Effects on Ecosystems (ICP Integrated Monitoring), ICP Modelling and Mapping, the International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops (ICP Vegetation) as well as of the International Cooperative Programme for Assessment and Monitoring of the Effects of Air Pollution on Rivers and Lakes (ICP Waters) and presented the progress of its work.

VII. Highlights of the scientific findings: policy-relevant issues

17. Examples of the most important of the 70 papers published in journals in 2021 that use ICP Forests data or the ICP Forests infrastructure are presented below. Key results that originated outside the ICP Forests community but are relevant to European forestry and are among the WGE priority topics are also presented in the following:

(a) A Europe-wide study[5] aimed to further improve both measurements and model-based estimates of sulfur (S) and nitrogen (N) deposition in Europe. Measured N and S depositions from EMEP and ICP Forests, two largely independent networks covering most of Europe, were compared with depositions calculated using the EMEP MSC-W model. N and S deposition compared well, in particular for low values where the effects of local sources are less important. For ammonium deposition local sources are more important, and measured deposition was generally lower than modelled. This pattern was even more evident in throughfall because of nitrogen retention in tree canopy. Long-term changes in precipitation acidity and the composition of acidifying compounds were evaluated using data from three different networks across North America, Europe, and East Asia. A general tendency towards increasing pH in North America and Europe owing to the reduction of SO_2 emissions were found[6]. With regard to N, deposition evolved from nitrate- to ammonium-dominated. Long-

[5] Aldo Marchetto and others. Good agreement between modeled and measured sulfur and nitrogen deposition in Europe, in spite of marked differences in some sites. *Frontiers in Environmental Science* No. 9, (September 2021).

[6] Chung-Te Chang and others. Changes of precipitation acidity related to sulfur and nitrogen deposition in forests across three continents in north hemisphere over last two decades. *Science of the Total Environment*, vol.806, 150552 (2022).

term trends of total (dry + wet) inorganic N deposition in Swedish forests were evaluated[7], showing somewhat larger decreases than expected based the decrease in the reported emissions in Europe. The need to include estimates of dry deposition in the assessment of N deposition in forests was emphasized;

(b) Critical loads for epiphytic macrolichens in US forests were reassessed and the interaction between effects of nitrogen (N) deposition, relative humidity, temperature and precipitation on lichen communities was studied[8]. Critical loads were estimated to be 1.5 kg ha^{-1} y^{-1} N deposition and 2.7 kg ha^{-1} y^{-1} S (sulfur) deposition, which is extremely low, confirming the high sensitivity to air pollution of this group of organisms. Interestingly, the study suggested that a reduction in N depositions could mitigate the expected negative effects of climate change on forest lichen communities;

(c) There is a general agreement about the need to adopt a flux-based risk assessment for the protection of European forests from tropospheric ozone. A study on the stomatal ozone fluxes carried out at low-elevation forest sites in Western Germany over the period 1998–2019 pointed out the importance to account for both ozone- and drought-induced effects on forest physiology and health: During growing seasons with sufficient water supply – and often lower ozone levels – forests are at higher ozone risk than during hot and dry periods[9]. As for the impact of ozone on vegetation, the integrated effect of climate and ozone fluxes on intra-annual tree ring increments of *Picea abies*, *Pinus sylvestris*, *Betula pendula*, and *Betula pubescens* was studied in the north-eastern part of Lithuania during the 2016–2018 period[10]. Surface ozone fluxes stimulated shrinking and inhibited the swelling of the tree stem, which resulted in a reduction of tree ring width in all tree species. Applying the ICP Forests protocol for assessment of leaf ozone injury, another study[11] found a significant correlation between the percentage of symptomatic plant species within the light exposed sampling site (LESS) and phytotoxic ozone dose (POD1), based on observations carried out at nine Level II Italian forest monitoring sites over 2017–2019. The results confirm the suitability of this plant-response indicator for the assessment of phytotoxic ozone levels in forests. In addition, a critical level of 11 mmol m^{-2} POD1 was recommended for forest protection against ozone injury. The appearance of visible symptoms on hybrid poplar leaves was preceded by microscopic necrosis that developed weeks before and at half the phytotoxic ozone dose[12]. Notwithstanding the initial visible injury to foliage, the treated poplars had still not shown any growth or biomass reduction. A simulation study[13] suggest a decrease of ozone due to air pollution control during the 21st century; this decrease, combined with the indirect effects of rising atmospheric CO2 concentration, which reduces stomatal uptake of ozone and increases water use efficiency, should lead to the decline of ozone-induced reductions in northern hemispheric gross primary production (GPP) and carbon uptake. However, in hot spot regions such as East Asia, the model simulations suggest a sustained decrease in GPP by more than eight per cent throughout the 21st century. Thus, it is important to continue the monitoring of ozone and the assessment of effects considering the possible role of other environmental factors;

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[7] Per Erik Karlsson and others. Twenty years of nitrogen deposition to Norway spruce forests in Sweden. *Science of the Total Environment,* vol.809, 152192 (2022).

[8] Linda H. Geiser and others. Lichen-based critical loads for deposition of nitrogen and sulfur in US forests. *Environmental Pollution*, vol. 291 (December 2021).

[9] Hannieh Egdami and others. Assessment of ozone risk to Central European forests: Time series indicates perennial exceedance of ozone critical levels. *Environmental Research,* vol. 203(1), 111798 (July 2021).

[10] Algirdas Augustaitis and others. Intra-annual variation of stem circumference of tree species prevailing in hemi-boreal forest on hourly scale in relation to meteorology, solar radiation and surface ozone fluxes. *Atmosphere,* vol. 12, 1017 (August 2021).

[11] Pierre Sicard and others. Testing visible ozone injury within a Light Exposed Sampling Site as a proxy for ozone risk assessment for European forests. *Journal of Forestry Research,* vol. 32, 1351–1359 (May 2021).

[12] Benjamin Turc and others. Dynamics of foliar responses to O_3 stress as a function of phytotoxic O_3 dose in hybrid poplar, *Frontiers in Plant Science* (June 2021).

[13] Martina Franz and Sönke Zaehle. Competing effects of nitrogen deposition and ozone exposure on northern hemispheric terrestrial carbon uptake and storage, 1850–2099. *Biogeosciences* (May 2021).

(d) After the drought years of 2018 and 2019, insights into tree responses emerged. Changes in tree growth in response to various environmental factors have therefore become increasingly important. Several studies investigated the response of beech (*Fagus sylvatica L.*) to drought and reported increased decline and mortality. For example, a Switzerland-wide study found that basal area increment in 2018 was significantly lower than the average annual increment in previous years[14];

(e) The temporal dynamics of understory vegetation responses to climate change was investigated in France[15]. A time lag in the response of temperate forest understory vegetation to warming climate was found: the velocity at which atmospheric air temperatures are rising is twice as fast as the velocity at which understory plant communities are responding. The lag in the response of herbaceous plant communities to climate warming increased linearly over time. Greater lags were observed in plots with warmer baseline temperature conditions, and in denser and older forests. No clear differences were found between coniferous and deciduous forests nor between inside and outside of the fenced forested sample plot area (effect of herbivores). However, forest disturbances and anthropogenic disturbances had a negative effect on the lag;

(f) Long-term ecosystem research continues to support that the N cycle interacts in a complex way with climate change and with all ecosystem compartments, among others soil, plants and microorganisms. When including climate change scenarios in future projections of carbon and nitrogen cycles, it is expected for German forest soils that the litter decomposition rates will increase[16]. Moreover, the decreasing trend in deposition since the 1990s seems to cause several changes in the nutrient balances in the forests. Soil solution chemistry continues to show decreasing sulphate concentrations but on the other hand an increasing trend in dissolved organic carbon[17],[18]. It was shown for beech stands in Germany that most of the deposited nitrogen is retained in the trees, especially in the stands on less acidic soils, and that 28 per cent is retained in the soil with high N/P and C/P ratios[19]. P limitation in European forest soils is observed in more and more studies[20], especially in combination with seasonal drought[21];

18. The ICP Forests Technical Report 2022 (see footnote 2.) presents results from 32 of the 42 countries participating in ICP Forests. Highlights of these results will be briefly discussed in the following subparagraphs:

(a) In 2020, acidifying, buffering and eutrophying compounds of open field bulk and below canopy throughfall deposition were analysed from 277 permanent plots and

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[14] Brigitte Rohner and others. Tree vitality indicators revealed a rapid response of beech forests to the 2018 drought. *Ecological Indicators* (2021).

[15] Benoit Richard and others. The climatic debt is growing in the understorey of temperate forests: Stand characteristics matter. *Global Ecology and Biogeography* (May 2021).

[16] Angela Schlutow and others. Modelling of soil characteristics as basis for projections of potential future forest ecosystem development under climate change and atmospheric nitrogen deposition. *Environmental Sciences Europe*, vol. 33 (August 2021).

[17] Arta Bārdule and others. Trends of Scots pine forest health and element flow changes in the ICP Forests monitoring sites in Latvia. *Baltic Forestry* 27(2), 199–215 (November 2021).

[18] Katarzyna Sawicka and others. Spatial properties affecting the sensitivity of soil water dissolved organic carbon long-term median concentrations and trends. *Science of the Total Environment* (August 2021).

[19] Rainer Brumme and others. Cycling and retention of nitrogen in European beech (Fagus sylvatica L.) ecosystems under elevated fructification frequency. *Biogeosciences* 18, 3763–3779, (June 2021).

[20] Enzai Du, Maarten van Doorn, and de Vries W. Spatially divergent trends of nitrogen versus phosphorus limitation across European forests. *Science of the Total Environment* 771,145391, (January 2021).

[21] Dolores Asensio and others. Simulated climate change and seasonal drought increase carbon and phosphorus demand in Mediterranean forest soils. *Soil Biology and Biochemistry* 163,108424 (December 2021).

following the ICP Forests Manual, in both the European ICP Forests network and the Swedish Throughfall Monitoring Network[22]:

(i) The uneven distribution of emission sources and receptors and the complex orography of parts of Europe results in a marked spatial variability of atmospheric deposition. However, on a broader scale, regional patterns in deposition arise. In the case of nitrate, high (>8 kg ha^{-1} y^{-1}) and moderate (4–8 kg ha^{-1} y^{-1}) throughfall deposition was mainly found in Central and Western Europe, including Austria, Belgium, Czech Republic, Germany, Italy, Poland and Slovenia, but single plots with high deposition values are also reported in other countries (e.g. Denmark or Sweden). The Central and Western European area of high (>8 kg ha^{-1} y^{-1}) and moderate (4–8 kg ha^{-1} y^{-1}) ammonium throughfall deposition is larger than for nitrate, with higher throughfall deposition values particularly in Germany, Belgium, and northern Italy, western Slovakia and Poland;

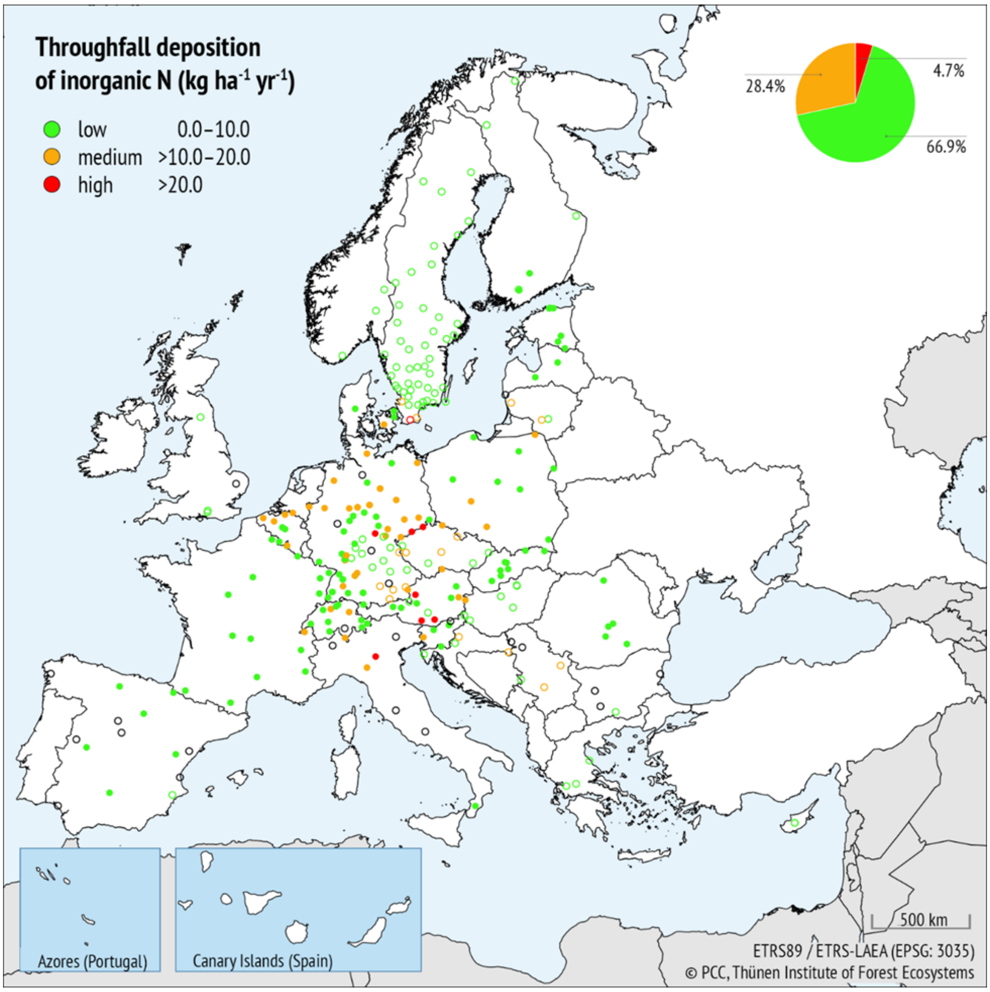
(ii) It is generally considered that negative effects of N deposition on forests become evident when inorganic N deposition (i.e. the sum of nitrate and ammonium deposition) is higher than the critical load. Critical loads can be evaluated for each site by modelling, but more generic critical loads (empirical critical loads) are also being evaluated,[23] ranging from 5 to 20 kg ha^{-1} y^{-1}. In 2020, throughfall inorganic N deposition higher than 10 kg ha^{-1} y^{-1} was mainly measured in Central and Western Europe, including Germany, Belgium, northern Italy, Switzerland, Austria, and Czech Republic (see figure I below). Occasionally, even N depositions larger than 20 kg ha^{-1} y^{-1} were observed in Germany, Austria and Italy. Total deposition of N is typically a factor 1 to 2 higher than (below canopy) throughfall deposition, due to N being taken up by tree leaves in the canopy.

[22] Aldo Marchetto and others. Atmospheric Deposition in European Forests in 2020. In Alexa Michel, Till Kirchner, Anne-Katrin Prescher and Kai Schwärzel, eds., “Forest Condition in Europe: 2022 Technical Report of ICP Forests. Report under the UNECE Convention on Long-range Transboundary Air Pollution” (forthcoming).

[23] Roland Bobbink and Jean-Paul Hettelingh, eds., *Review and revision of empirical critical loads and dose-response relationships: Proceedings of an expert workshop, Noordwijkerhout (Netherlands), 23–25 June 2010* (Coordination Centre for Effects/National Institute for Public Health and the Environment of the Netherlands, 2011).

Figure I

Throughfall deposition of inorganic nitrogen (NO3--N + NH4+-N) (kg N ha-1 yr-1) measured in 2020 on the ICP Forests Level II plots and the Swedish Throughfall Monitoring Network



Notes: Coloured dots, validated data; Coloured circles, unvalidated data; Black circles, monitoring period shorter than 330 days.

(b) Tree crown defoliation and occurrences of biotic and abiotic damage are important indicators of forest condition. As such, they are considered within Criterion 2 "Forest health and vitality", one of the six criteria adopted by Forest Europe (formerly the Ministerial Conference on the Protection of Forests in Europe) to provide information for sustainable forest management in Europe:

(i) The transnational crown condition survey in 2021[24] was conducted on 106,451 trees on 5,565 plots in 27 countries. Out of those, 101,663 trees were assessed in the field for defoliation. The overall mean defoliation for all species was 23.5 per cent in 2021; there was no change for broadleaves and a very slight increase in defoliation for conifers in comparison with 2020. Broadleaved trees showed a higher mean defoliation than coniferous trees (23.4 versus 22.4 per cent, respectively). Correspondingly, conifers had a higher frequency of trees in the "none" and "slight" defoliation classes (72.9 per cent combined) than broadleaves (70.0 per cent) and a

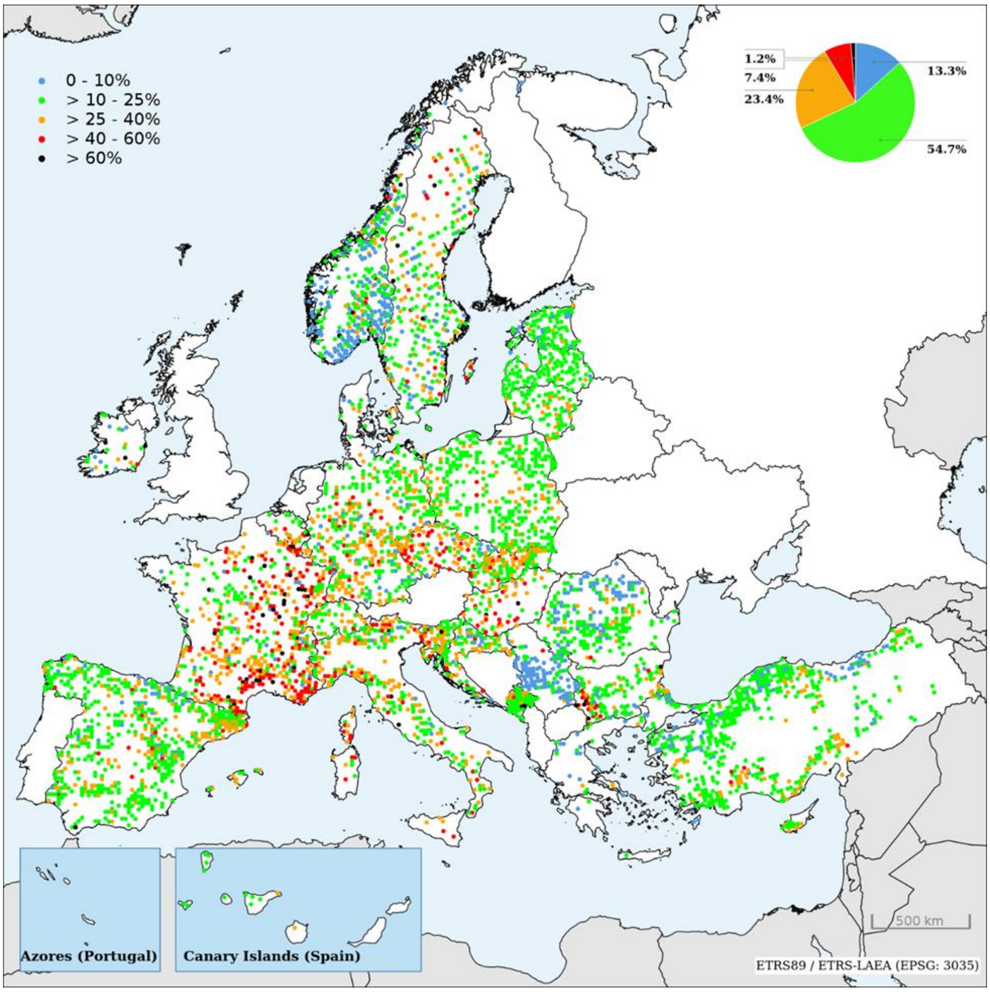
[24] Volkmar Timmermann and others, "Tree crown condition in 2021" in Alexa Michel, Till kirchner, Anne-Katrin Prescher and Kai Schwärzel, eds., "Forest Condition in Europe: 2022 Technical Report of ICP Forests. Report under the UNECE Convention on Long-range Transboundary Air Pollution" (forthcoming).

lower frequency of trees with more than 60 per cent defoliation (2.5 versus 4.2 per cent);

(ii) Mean defoliation of all species at plot level in 2020 is shown in figure II below. More than two thirds (68 per cent) of all plots had a mean defoliation up to 25 per cent, and only 1.2 per cent of the plots showed severe defoliation (more than 60 per cent). While plots with defoliation up to 10 per cent were located mainly in Norway, Serbia, Romania and Türkiye, plots with slight mean defoliation (11–25 per cent) were found across Europe. Clusters of plots with moderate to severe mean defoliation were found from the Pyrenees through southeast (Mediterranean) France to western Italy, but also from central and northern France through Germany and into Czech Republic, Slovakia and Hungary, as well as in western Bulgaria and coastal Croatia.

(iii) In a study carried out on ICP Forests Level II plots I France, a distinct correlation was found between defoliation and basal area increment (BAI), with an approximate 1% reduction of BAI per unit increase of defoliation. This may have substantial implications when linking forest health and the climate change mitigation potential of European forests.[25]

Figure II
Mean plot defoliation of all species in 2020



Notes: The legend (top left) shows defoliation classes ranging from none (blue), to slight (green), to moderate (orange and red), to severe (black). The percentages refer to the needle/leaf loss in the crown

[25] Marco Ferretti and others. Tree canopy defoliation can reveal growth decline in mid-latitude temperate forests. *Ecological Indicators* 127, 107749 (2021).

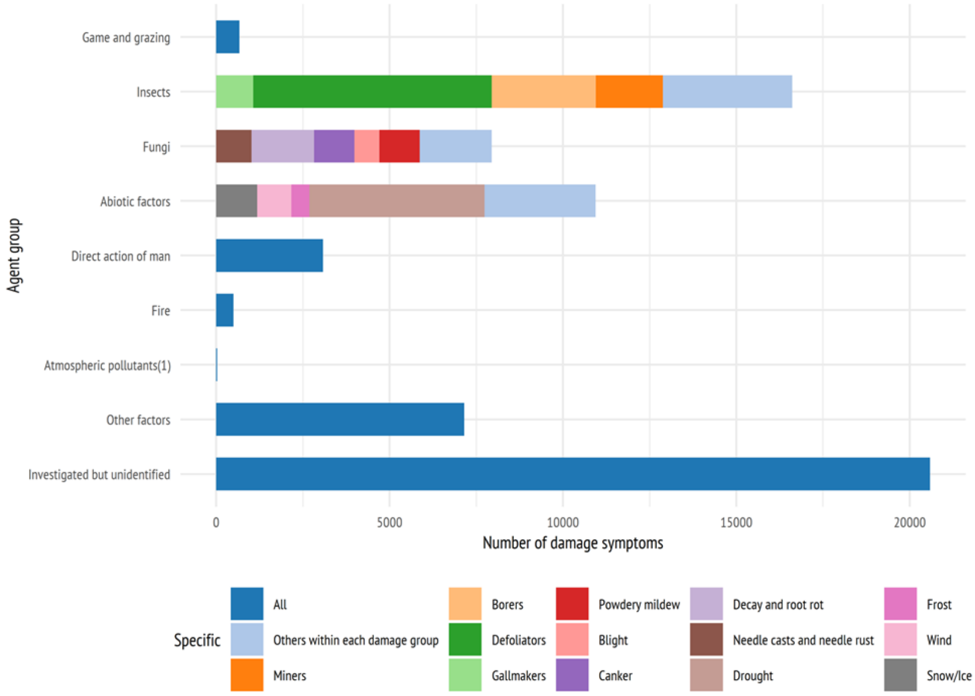
compared to a reference tree. The pie chart (top right) shows the percentage of plots per defoliation class. Dead trees are not included.

(c) Combining the assessment of damage symptoms and their biotic and abiotic causes with observations of defoliation allows for a better insight into the condition of trees, and the interpretation of the state of European forests and its trends in time and space is made easier:

(i) In 2021, investigation of causes of damage were carried out on 100,732 trees on 5,459 plots and in 26 countries. On 46,790 trees (46.4 per cent), at least one symptom of damage was found, which is 0.8 per cent less than in 2020 (47.2 per cent). In total, 67,509 observations of damage were recorded (multiple damage symptoms per tree were possible). Both fresh and old damage was reported. Most of the reported damage symptoms were observed on the leaves of broadleaved trees (30.0 per cent), followed by twigs and branches (28.8 per cent) and stems (21.4 per cent). Needles were also often affected (13.5 per cent), while roots, collar, shoots, buds and fruits of both broadleaves and conifers were less frequently affected. More than half (53.8 per cent) of all recorded damage symptoms had an extent of up to 10 per cent, 37.4 per cent had an extent between 10 per cent and 40 per cent, and 8.9 per cent of the symptoms covered more than 40 per cent of the affected part of a tree;

(ii) Figure III below shows that insects were the predominant cause of damage and responsible for 24.6 per cent of all recorded damage symptoms on level I plots across Europe. Abiotic agents were the second major causal agent group responsible for 16.2 per cent of all damage symptoms. Within this agent group, roughly half of the symptoms (46.2 per cent) were attributed to drought, while snow and ice caused 10.8 per cent, wind 9.0 per cent, and frost 4.7 per cent of the symptoms. Fungi were the third major causal agent group, with 11.8 per cent of all damage symptoms.

Figure III
Number of damage symptoms according to agent groups and specific agents/factors



Notes: Multiple damage symptoms per tree were possible, and dead trees are included (n=67,509). (1) Visible symptoms of direct atmospheric pollution impact only.

VIII. Publications

19. For a full list of all 70 ICP Forests publications using ICP Forests data or the ICP Forests infrastructure in peer-reviewed journals and references for the present report, please refer to the ICP Forests Technical Report 2022, or visit the ICP Forests website.[26]

[26] See http://icp-forests.net/page/publications.