Forest Condition in Europe

The 2024 Assessment

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

LRTAP Long-range Transboundary Air Pollution

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

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ICP FORESTS

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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)
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Cover photo by Tanja Sanders | Thünen Institute of Forest Ecosystems

Recommended citation

Michel A, Haggenmüller K, Kirchner T, Prescher A-K, Schwärzel K, Wohlgemuth L, editors (2024) Forest Condition in Europe: The 2024 Assessment. ICP Forests Technical Report under the UNECE Convention on Long-range Transboundary Air Pollution (Air Convention). Eberswalde: Thünen Institute. 96 p. https://doi.org/10.3220/ICPTR1732702585000

ISSN 1020-3729 (print) ISSN 2702-5411 (online)
ISBN 978-3-86576-282-5 DOI 10.3220/ICPTR1732702585000

2

FOREST CONDITION AND ENVIRONMENTAL DRIVERS IN EUROPE – RECENT EVIDENCE FROM SELECTED STUDIES

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Introduction

Marco Ferretti, Lars Vesterdal, Marcus Schaub, Kai Schwärzel

Forests are increasingly threatened by climate change-related factors, and the knowledge and understanding of forest dynamics is necessary to identify management solutions for forest resilience while maintaining biodiversity and provision of ecosystem services. Continued monitoring is essential to document progress to reduce air pollution impacts on forests, an important factor affecting the health and sustainability of forest ecosystems around the world, especially under the concurrent pressure exerted by annual meteorological fluctuations and long-term climate change.

The data generated by the monitoring networks installed under ICP Forests demonstrates its high relevance at scientific and political levels. The ecosystem-oriented approach includes the main biotic and abiotic stressors that may impact our forests, and therefore enables identification of the role of air pollution. Yet, it is important to contextualize ICP Forests results within the larger picture offered by studies originating from other research and monitoring initiatives.

Here we present a brief overview prepared by the Expert Panels (EPs) and edited by the Scientific Committee of ICP Forests. EPs were asked to provide an overview of main evidence and key findings in their subject areas over the past year with particular focus on prioritized topics of the Working Group on Effects (WGE) under the UNECE Air Convention: nitrogen (N) deposition, ozone (O_3), heavy metals and air pollution-climate change interactions. EPs based their input on scientific publications that were selected if (1) peer-reviewed; (2) from the reporting year or the year before, if not yet included; (4) covering emerging issues; and (5) relevant to the UNECE Air Convention.

In the following, we summarize the main evidence according to three main ecosystem compartments: atmosphere, forest vegetation, and forest soil. Given the interrelationships and the continuous fluxes and cycles of pollutants, carbon, water and nutrients across the three compartments, some overlap exists among the different chapters. Connection and interrelationships are particularly important in view of the interactions between the abiotic and biotic environment, and specifically for air pollution, deposition, climate change, and extreme events.

Recent evidence from selected studies

ATMOSPHERE

Atmospheric deposition

Arne Verstraeten, Peter Waldner, Andreas Schmitz, Aldo Marchetto

Two studies at European scale provided new insights into forest ecosystem N cycling. Guerrieri et al. (2024) found evidence of substantial canopy nitrification through the analysis of the natural $\Delta^{17}O$ isotopic tracer in bulk precipitation and throughfall collected in beech and Scots pine stands across an N deposition gradient based on ten ICP Forests Level II plots. Additional genetic analysis of foliar samples enabled identification of archaea and specialized bacteria as the main taxa governing this process. Strikingly, the results imply that throughfall deposition probably underestimates the share of reduced N (NH_4^+) in total deposition and, ultimately, its impact on forest ecosystems. Findings are also relevant to the debate on widespread ecosystem N saturation versus ecosystem oligotrophication and can be used to improve canopy budget models. Verstraeten et al. (2023) compared throughfall deposition fluxes during the spring in homogeneous stands of beech, oak, spruce, and pine with airborne pollen concentrations of the dominant tree genus measured in nearby cities. Particularly for beech they found a positive relationship between the airborne pollen concentrations and throughfall fluxes of potassium, ammonium, organic nitrogen, and carbon. On the other hand, the results indicated that pollen or associated micro-organisms can reduce the amount of nitrate in throughfall. From this it can be concluded that the estimation of throughfall element fluxes is significantly affected by tree pollen.

Two studies conducted in Greek forests focused on the cycling and status of boron and cobalt respectively (Michopoulos et al. 2023a, 2023b). They are remarkable because these elements are not included in the standard list of parameters commonly assessed in the ICP Forests deposition survey, but both are essential plant micronutrients. Evidence was found that small amounts of boron and cobalt undergo long-range transport through the atmosphere and reach the forest canopy mainly through dry deposition.

Ambient air quality

Diana Pitar, Elena Gottardini

In the last year, air quality research and monitoring activities focused on determining pollutant trends, especially ozone and its precursors, using models in which in situ and remote sensing data serve as inputs (Gaudel et al. 2024, Wang et al. 2024). Also, Shah at al. (2024) found that ozone trends increase not only due to its "traditional precursors", but also due to increased particulate nitrate photolysis. Considering climate change and air pollution changes, statistical downscaling projects decreasing ground-level ozone concentrations in the European area under the moderate SSP2-4.5 scenario, but increasing concentrations under the pessimistic SSP3-7.0 scenario (Hertig et al. 2023). Therefore, the effects of ozone on vegetation may become more and more pronounced. In line with this, Ferretti et al. (2024) showed that high summer ozone concentrations and foliar symptoms slightly decreased in European forests over the period 2005–2018. Ozone concentrations were higher in the Mediterranean and the Alpine biogeographic regions. Ozone has a significant effect on symptoms in the most sensitive species. Also, it was shown that symptoms tend to be driven by functional leaf traits.

FOREST VEGETATION

Forest growth

Tanja Sanders, Monika Vejpustková

Over the last years forests across Europe have shown increasing mortality and overall decreasing growth (Vacek et al. 2023, Rybar et al. 2023). This trend, driven by hotter droughts, is modified by nitrogen deposition as reported in a study by Dietrich et al. (2024). Several tree species in Central Europe change their response to climate at high nitrogen input, albeit in both directions. Similar results were found in a study by Cuciurean et al. (2024) who investigated the input of air pollution on forests. They found that pollutants impaired tree growth and that trees accumulated heavy metals in the wood, the concentrations of which decreased over time as pollution decreased.

In general, annual growth reductions of around 40% were found across all trees since 2018 (Thom et al. 2023). However, the variations among individuals and species were quite high (Thom et al. 2023) and large differences were found at a regional and species-specific level (Pretzsch et al. 2023). One of the species with growth reduction seems to be European beech (*Fagus sylvatica*) showing a marked decline under drought conditions (Rukh et al. 2023) and high nitrogen input (Karlsson et al. 2023, Dietrich et al. 2024).

Overall, the development towards more extreme temperatures and recurring droughts has a measurable impact on Europe's forests. While some species benefit from the rising temperatures, some will decline under the drier conditions and the picture of our forest will therefore continue to change.

Forest health

Nenad Potočić, Volkmar Timmermann

Recurrent climate-driven disturbances impact the health of European forests, which respond with increased tree crown defoliation, dieback, and mortality. Prompted by numerous reports on European beech suffering from severe growth reductions, early leaf senescence, leaf browning, and crown dieback, a paper by Rukh et al. (2023) explored the resistance of European beech to climate change, comparing the effects of major recent (2003 and 2018/2019) droughts in Central Europe. The results point to the conclusion that enhanced drought exposure of beech trees could push them beyond their hydraulic safety margins, with synergistic effects of drought-related impacts potentially leading to lower recovery and subsequent tree death. In order to better predict the future beech vitality in Central Europe, the authors recommend investigating both short- and long-term legacy effects of defoliation and its influence on growth after droughts.

Tree crown defoliation is the most widely used parameter for monitoring forest health, however, it is not a cause-specific indicator of tree vitality. On the contrary, physiological processes associated with defoliation can affect a tree's water relations, photosynthesis and carbon metabolism, growth, and nutrient balance. Bussotti et al. (2024) discussed relations of defoliation with various underlying physiological processes, environmental impacts, and other established vitality parameters, and suggested the inclusion of various physiological variables into forest monitoring that would enhance our level of understanding of the causes of tree decline and provide data to feed process-based models to predict forest tree mortality.

Tree mortality is an objective forest health indicator particularly suitable for long-term and large-scale studies of forest condition. Mortality rates, however, can be subject to different interpretations, related mostly to whether the trees removed in forest operations are included in the definition of mortality. An additional difficulty stems from the nature of forest monitoring, where assessments are repeated in annual or even multi-annual cycles, and the actual reasons for the removal of trees are unknown, i.e., we cannot determine whether trees were alive or dead at the time of extraction. Using data from the annual Level I surveys in Poland from 2009 to 2022 for pine, spruce, oak, and birch, Lech and Kamińska (2024) found that the calculated mortality rates depended on how removals were treated in the analysis. Based on data on defoliation and the severity of damage assessed prior to tree removal, the authors suggest that trees removed by sanitation cuts should be included when calculating mortality in managed forest stands.

Forest nutrition

Liisa Ukonmaanaho, Lena Wohlgemuth

Common beech (*Fagus sylvatica*) is an ecologically and economically important tree species of European forests, which has been suffering from recent drought events due to climate change. Beech foliar nutritional status can serve as an insightful indicator to monitor the vitality of this common tree species and perform damage assessments. In this context, two recent studies have addressed impacts on beech health under varying climatic conditions/drought using foliar nutrient analysis.

Based on 28 beech plots of the ICP Forests Level I network, Ognjenović et al. (2023) found that differences in beech foliar nutrient concentrations between trees of high and low defoliation rate are influenced by climatic parameters such as mean/maximum annual temperature and mean annual precipitation as well as environmental parameters such as altitude, soil silt fraction, and soil exchangeable calcium (Ca). Examples of these differences include foliar Ca, for which the odds of low defoliation beech trees to exhibit high foliar Ca concentrations was found to be 90% higher with increasing mean annual precipitation than for high defoliation beech trees. However, a universal relation between foliar nutrition and defoliation of beech could not be established based on the investigated data, which was limited to Croatia in geographic extent. More research on the impact of environmental factors on foliar nutrition is therefore necessary including climatic gradients of a wider geographic area.

Marušić et al. (2023) investigated how drought conditions impact nutrient uptake by beech saplings and how the interplay between nutrient availability and drought stress affects physiology, growth, and biomass accumulation of young beech trees. Among other observations, the authors detected that foliar nitrogen and potassium concentrations were affected in saplings previously exposed to prolonged drought, regardless of fertilization dose. During the course of drought, fertilization significantly lessened the immediate effect of drought on foliar nitrogen concentrations. Fertilization also played a significant role in the recovery of phosphorus levels after drought, emphasizing the importance of phosphorus availability for beech forest vitality.

Meteorological trends and effects on forests

Stefan Fleck, Stephan Raspe, Lothar Zimmermann

A review on impacts and damages of the European multi-year drought and heat event 2018–2022 on forests (Knutzen et al. 2023) combined information on European-wide SPEI maps of summer respectively spring and summer for these years with country-specific information on forest damage as well as ICP Forests data. Damage by heat and drought was categorized by physiological reasons, pests, and forest fires. The following trends were derived: (1) Relative defoliation rates of broadleaves are higher than that of conifers in every country with the exception of Czechia; (2) the incidence of wood destroyed by insects is extremely high in central Europe and Sweden; (3) although forest fires can be related to heat and drought, they are superimposed by other anthropogenic influences; (4) forests in central Europe were particularly affected, while forests in the northern and Alpine zones were less affected, and adaptations to heat and drought can still be observed in the southern zone; (5) although 2021 was an average year in several regions, high levels of damage were still observed indicating strong legacy effects of 2018–2020.

In a methodological study on interception in two even-aged (40–60 years) temperate oak (deciduous) and Norway spruce (coniferous) forests in Denmark, Andreasen et al. (2023) report precipitation and throughfall for 13 and 11 months, respectively. One site was part of the ICP Forests Level II programme, the other was part of the Integrated Carbon Observation System ICOS. Canopy structure parameters relevant for interception were derived from these data. The observation-based interception loss was compared to predictions obtained by the analytical Gash interception model using the derived canopy structure parameters. One year with the same precipitation was simulated at both sites (526 mm), and the interception loss was 35% for the deciduous forest and 51% for the coniferous forest. These simulated values were similar to field observations of interception loss amounting to 35% in the deciduous and 46% in the coniferous forest. As a main result, improved agreement between observation-based and predicted interception loss is obtained in the deciduous forest using canopy structure parameters for the leafless and full-foliage periods instead of annual average values.

Forest species composition and diversity

Leena Hamberg

Occupancy patterns of birds, mammals, plants, and phytoplankton between protected and unprotected sites in Finland were investigated across four decades (Santangeli et al. 2023). Mixed impacts of protected areas were found, with only a small proportion of species explicitly benefiting from protection, mainly through slower rates of decline inside protected areas. The results suggested that the current protected area network can partly contribute to slow down species declines, but alone they will not suffice to halt the biodiversity crisis. Thus, coverage, connectivity, and management should be improved to enhance the efficiency of protected areas towards bending the curve of biodiversity loss. Protection can contribute to shape species occurrences, but the effects are highly species-specific and depend on key features of the protected areas, such as the timing of protection and the size of the protected area.

In coniferous forests in Finland, the effects of broadleaved tree admixture, tree species richness, stand density, and shrub cover on the number of vascular plant species were studied by using data from ICP Forests Level I sample plots in 2006 (Salemaa et al. 2023). Vascular species richness and herb cover generally increased with increasing proportion of broadleaved trees and tree species richness, but high stand density and extensive shrub cover reduced the positive biodiversity effects. An increase in proportion of broadleaved trees correlated positively with calcium and negatively with C:N of the organic layer, and therefore, nutrient input from easily decomposable birch leaf litter was considered to promote species richness and herb cover via improved nutrient availability in the soil.

Bryophytes growing on different substrates were identified in ICP Forests Level I and Level II monitoring plots in close-to-nature managed forests in Slovenia (Kutnar et al. 2023a). The bedrock and tree species composition were important drivers of bryophyte species diversity and composition. Functional diversity and composition of bryophytes were also significantly affected by bedrock and soil, but somewhat less so by tree species composition. In another study, Kutnar et al. (2023b) compared species richness and trait diversity as well as species composition and trait composition between vascular plant and bryophyte assemblages. The number of all bryophytes was positively correlated with vascular species richness. However, since both congruences and discrepancies in the drivers controlling the diversity and composition of the two groups at taxonomic and functional trait levels were found, the authors recommended long-term maintenance of the structural and compositional heterogeneity of stands also in the future.

A study in Italy revealed that the sampling approach of ICP Forests Level I plots performed better in estimating understory vascular plant species richness and diversity than the sampling approach called preferential sampling (Alessi et al. 2023). In the preferential approach, vegetation plots were selected at environmentally homogeneous sites on the basis of expert selection, and variable numbers and sizes of plots were used to characterize plant communities. The preferential approach, including a larger set of sample plots, was better in detecting forest specialist species and plant diversity hotspots. Based on the results, the authors suggested that both sampling approaches could be used in combination for better conservation and monitoring to detect multiple aspects of plant community diversity.

FOREST SOIL

Nathalie Cools, Bruno De Vos, Tiina M. Nieminen

In Italy, Andreetta et al. (2023) showed that the soil type is an important environmental factor to explain soil organic carbon storage across ICP Forests Level I plots. However, in boreal forests Merilä et al. (2023) showed the relative importance of tree species along a latitudinal gradient based on ICP Forests Level II plots. In France, Saenger et al. (2024) found a significant increase in the surface soil carbon stock between two ICP Forests Level II soil inventories. Conversely the relative increase of the total nitrogen stocks was lower in the surface soil and a general and sharp decline of total nitrogen was detected in the subsoil. These results led to a substantial increase in C/N ratio over the whole soil profile. A second finding was that the recovery from soil acidification depends on the initial base saturation status. In highly acidified contexts, increased soil acidification over the profile was observed, while exchangeable base cation pools increased. On the other hand, less acidic soils saw their global buffer capacity enhanced.

In Sweden, Karlsson et al. (2024) found that the reduced deposition load has improved the acidification status of the soil solution but the forest ecosystems are far from fully recovered, with low buffering capacity (ANC – Anion Neutralising Capacity) and thus show low resilience towards inputs of acidity. The sulphur concentrations in the soil solution have decreased, and on many of the most acidified sites ANC has increased substantially but is still below zero. Several less acidified sites have increased pH values in soil solution, but there are also some examples of decreased pH values. Forest ecosystems in southwest Sweden are often close to N saturation, with frequent leakage of NO_3 from the root zone, which does not appear to have changed over the last 35 years. It is concluded that continued monitoring of soil water chemistry is important to follow the forest soil recovery progress in a changing climate.

It becomes more and more evident that the forest soil microbiome, i.e., bacteria, archaea, and fungi, plays an essential role in response to eutrophication caused by nitrogen deposition. Baldrian et al. (2023) found that nitrogen deposition substantially affects the forest soil microbial processes, especially in the temperate zone. The soil microbiome drives multiple crucial steps in the biogeochemical cycles (Meena et al. 2023). Several studies highlight the relative importance of the fungal communities. Based on DNA sequencing of soil samples from 238 ICP Forests Level II plots across a northeast–southwest gradient in Europe, Anthony et al. (2024) demonstrated that fungal, but not bacterial, composition and richness are correlated with tree growth rates and tree biomass carbon stocks. In France, Cissé et al. (2023) found that glomalin-related soil protein (GRSP), thought to be of fungal origin, makes up a distinct fraction of soil organic matter (SOM) in forest soils. Digging deeper into plant-microorganism-soil interactions will help to predict the future of forests and identify management strategies to increase ecosystem stability and alleviate climate change effects. Currently soil biota and their functioning are not included in the ICP Forests soil monitoring programme, however, recent scientific findings provide strong arguments for inclusion of soil biota community and diversity indicators in the future monitoring programme.

Conclusions

Marco Ferretti, Lars Vesterdal, Marcus Schaub

Climate change is dramatically affecting our forests, together with lasting effects of air pollution and acidification. On one side, there are reports of widespread increased tree mortality and reduced growth, although with some regional differences. On the other side, the complex dynamics of air pollution across forest ecosystems, and the complexity of related measurements, have been pointed out. In synthesis:

- Canopy processes, phenology, and leaf traits can have an important role for the measured deposition levels, e.g., on N-related species and other nutrients, and on the onset of ozone visible symptoms.

REVIEW

- Despite some stagnation of the temporal trend in ozone concentration, ozone is still causing visible symptoms on a variety of broadleaved species.
- Forest health and growth were extensively affected, mostly by climate-change related factors but also in combination with atmospheric deposition of N and foliar nutrition, although with yet unclear patterns.
- In terms of biodiversity, the role of the composition of the tree species layer, the stand structure, the shrub coverage, and the bedrock were found important for vascular species and Bryophytes.
- In parts of Europe, soil has not yet recovered from previous high acidification loads. Soil type and tree species have been confirmed as strong drivers of soil carbon stocks across Europe, and dynamics observed in soil carbon differed between topsoil and subsoil. In addition, soil microbiota is emerging more and more as an important driver of forest growth – and likely of forest health.

ICP Forest is unique in its role as a pan-European, science-based monitoring programme and shows how maintenance of up-to-date information on tree vitality status and trends is fundamental. The combined detection of changes and the process understanding is highly needed to build future resilient forests.

References

Alessi N, Bonari G, Zannini P, et al. (2023) **Probabilistic and preferential sampling approaches offer integrated perspectives of Italian forest diversity.** Journal of Vegetation Science 34: e13175. https://doi.org/10.1111/jvs.13175

Andreasen M, Christiansen JR, Sonnenborg TO, et al. (2023) **Seasonal dynamics of canopy interception loss within a deciduous and a coniferous forest.** Hydrological Processes 37(4), e14828. https://doi.org/10.1002/hyp.14828

Andreetta A, Chelli S, Bonifacio E, et al. (2023**) Environmental and pedological factors influencing organic carbon storage in Italian forest soils.** Geoderma Regional 32:e00605. https://doi.org/10.1016/j.geodrs.2023.e00605

Anthony MA, Tedersoo L, De Vos B., et al. (2024) **Fungal community composition predicts forest carbon storage at a continental scale.** Nat Commun 15, 2385. https://doi.org/10.1038/s41467-024-46792-w

Baldrian P, López-Mondéjar R, Kohout P (2023) **Forest microbiome and global change.** Nat Rev Microbiol 21:487–501. https://doi.org/10.1038/s41579-023-00876-4

Bussotti F, Potočić N, Timmermann V, et al. (2024) **Tree crown defoliation in forest monitoring: concepts, findings, and new perspectives for a physiological approach in the face of climate change.** Forestry: An International Journal of Forest Research, cpad066.

Cissé G, Essi M, Kedi B, et al. (2023) **Accumulation and vertical distribution of glomalin-related soil protein in French temperate forest soils as a function of tree type, climate and soil properties.** CATENA 220:106635. https://doi.org/10.1016/j.catena.2022.106635

Cuciurean CI, Sidor CG, Camarero JJ, et al. (2024) **Detecting changes in industrial pollution by analyzing heavy metal concentrations in tree-ring wood from Romanian conifer forests.** Environmental Research, 118884.

Dietrich V, Lauritz M, Roggenhofer MM, et al. (2024) **Drought effects on growth and density of temperate tree regeneration under different levels of nitrogen deposition.** Forest Ecology and Management 559, 121825.

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/https://doi.org/10.1016/j.ecolind.2023.111486

Gaudel A, Bourgeois I, Li M, et al. (2024) **Tropical tropospheric ozone distribution and trends from in situ and satellite data.** EGUsphere, 2024, 1-51.

Guerrieri R, Càliz J, Mattana S, et al. (2024) **Substantial contribution of tree canopy nitrifiers to nitrogen fluxes in European forests.** Nature Geoscience 17, 130–136. https://doi.org/10.1038/s41561-023-01364-3

Hertig E, Jahn S, Kaspar-Ott I (2023) **Future local ground-level ozone in the European area from statistical downscaling projections considering climate and emission changes.** Earth's Future 11, e2022EF003317. https://doi.org/10.1029/2022EF003317

Karlsson GP, Akselsson C, Hellsten S, Karlsson PE (2024) **Atmospheric deposition and soil water chemistry in Swedish forests since 1985 – Effects of reduced emissions of sulphur and nitrogen.** Science of The Total Environment 913:169734. https://doi.org/10.1016/j.scitotenv.2023.169734

Karlsson PE, Pleijel H, Fowler P, et al. (2023) **Stem growth of Norway spruce in south Sweden in relation to soil moisture, nitrogen deposition, ozone exposure and meteorological variables.** Forest Ecology and Management 549, 121455.

Knutzen F, Averbeck P, Barrasso C, et al. (2023**) Impacts and damages of the European multi-year drought and heat event 2018–2022 on forests, a review**. EGUsphere [preprint], https://doi.org/10.5194/egusphere-2023-1463

Kutnar L, Kermavnar J, Sabovljević MS (2023a) **Bryophyte diversity, composition and functional traits in relation to bedrock and tree species composition in close-to-nature managed forests.** European Journal of Forest Research 142: 865–882. https://doi.org/10.1007/s10342-023-01560-1

Kutnar L, Kermavnar J, Sabovljević MS (2023b) **Congruence between vascular plants and bryophytes in response to ecological conditions in sustainably managed temperate forests (taxonomic- and trait-based levels).** Plant Ecology 224: 1001–1014. https://doi.org/10.1007/s11258-023-01357-7

REVIEW

Lech P, Kamińska A (2024) **"Mortality, or not mortality, that is the question…": How to treat removals in tree survival analysis of central European managed forests.** Plants, 13(2), 248.

Marušić M, Seletković I, Ognjenović M, et al. (2023**) Nutrient and growth response of *Fagus sylvatica* L. saplings to drought is modified by fertilisation.** Forests 14(12),2445. https://doi.org/10.3390/f14122445

Meena M, Yadav G, Sonigra P, et al. (2023**) Multifarious responses of forest soil microbial community toward climate change.** Microb Ecol 86:49–74. https://doi.org/10.1007/s00248-022-02051-3

Merilä P, Lindroos A-J, Helmisaari H-S, et al. (2024**) Carbon stocks and transfers in coniferous boreal forests along a latitudinal gradient.** Ecosystems 27:151–167. https://doi.org/10.1007/s10021-023-00879-5

Michopoulos P, Kostakis M, Koulelis P, et al. (2023a) **Cycling and status of boron in two forest types in Greece.** Ann. For. Res. 66, 113–122. https://doi.org/10.15287/afr.2023.2940

Michopoulos P, Kostakis M, Kaoukis K, et al. (2023b) **Cycling and status of cobalt in some forest types.** Folia Oecologia 50, 72–79. https://doi.org/10.2478/foecol-2023-0006

Ognjenović M, Seletković I, Marušić M, et al. (2022) **The effect of environmental factors on the nutrition of European beech (*Fagus sylvatica* L.) varies with defoliation.** Plants 12(1), 168. doi: 10.3390/plants12010168.

Pretzsch H, Del Río M, Arcangeli C, et al. (2023) **Forest growth in Europe shows diverging large regional trends.** Scientific Reports, 13(1), 15373.

Rukh S, Sanders TG, Krüger I, et al. (2023) **Distinct responses of European beech (*Fagus sylvatica* L.) to drought intensity and length—a review of the impacts of the 2003 and 2018–2019 drought events in Central Europe.** Forests, 14(2), 248.

Rybar J, Sitková Z, Marcis P, et al. (2023) **Declining radial growth in major western Carpathian tree species: insights from three decades of temperate forest monitoring.** Plants 12(24), 4081.

Salemaa M, Hotanen J-P, Oksanen J, et al. (2023) **Broadleaved trees enhance biodiversity of the understorey vegetation in boreal forests.** Forest Ecology and Management 546: 121357. https://doi.org/10.1016/j.foreco.2023.121357

Santangeli A, Weigel B, Antão LH, et al. (2023**) Mixed effects of a national protected area network on terrestrial and freshwater biodiversity.** Nature Communications 14: 5426. https://doi.org/10.1038/s41467-023-41073-4

Saenger, A.0, André, F., Jonard, M., Nicolas, M. and Ponette, Q. (2024) **Carbon sequestration and nitrogen loss drive the evolution of French forest soils.** Front. For. Glob. Change 7:1338239. https://doi.org/10.3389/ffgc.2024.1338239

Shah V, Keller CA, Knowland KE, et al. (2024**) Particulate nitrate photolysis as a possible driver of rising tropospheric ozone.** Geophysical Research Letters 51, e2023GL107980. https://doi.org/10.1029/ 2023GL107980

Thom D, Buras A, Heym M, et al. (2023) **Varying growth response of Central European tree species to the extraordinary drought period of 2018–2020.** Agricultural and Forest Meteorology 338, 109506.

Vacek Z, Vacek S, Cukor J (2023) **European forests under global climate change: Review of tree growth processes, crises and management strategies.** Journal of Environmental Management 332, 117353.

Verstraeten A, Bruffaerts N, Cristofolini F, et al. (2023) **Effects of tree pollen on throughfall element fluxes in European forests.** Biogeochemistry 165, 311–325. https://doi.org/10.1007/s10533-023-01082-3

Wang J, Ju T, Li B, et al. (2024) **Characterization of tropospheric ozone pollution, random forest trend prediction and analysis of influencing factors in south-western Europe.** Environ Sci Eur 36, 61. https://doi.org/10.1186/s12302-024-00863-3