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2025

Forest Condition in Europe

The 2025 Assessment

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

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Convention on Long-range Transboundary Air Pollution

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ATMOSPHERIC DEPOSITION IN EUROPEAN FORESTS IN 2023

Aldo Marchetto, Arne Verstraeten, Peter Waldner, Andreas Schmitz, Alexa Michel, Katrin Haggenmüller, Till Kirchner

Introduction

The atmosphere contains a large number of substances of natural and anthropogenic origin. A large fraction of these substances can settle, be adsorbed to receptor surfaces, or be included in rain and snow, and eventually reach the land surface as wet and dry deposition. In the last century, human activities led to a dramatic increase in the deposition of nitrogen and sulphur compounds, reaching peak levels approximately in the 1970s–80s.

Sulphur deposition today occurs almost completely in the form of sulphate (SO_4^{2-}), derived from marine aerosol and from sulphuric acid formed in the atmosphere by the interaction of gaseous sulphur dioxide (SO_2) with water. SO_2 emissions result from anthropogenic combustion processes, volcanoes, and forest fires and have increased since the 1850s in the wake of the Industrial Revolution, causing an increase in sulphate deposition and deposition acidity. This can, however, be partially buffered by the deposition of base cations, mainly calcium (Ca^{2+}) and magnesium (Mg^{2+}).

Natural sources of nitrogen (N) in the atmosphere are mainly restricted to the emission of laughing gas (N_2O) and molecular nitrogen gas (N_2) during denitrification and the conversion of N_2 into NO_X during lightning. However, human activities cause high emissions of nitrogen oxides (NO and NO_2, together called NO_x) during combustion processes, and of ammonia (NH_3) from agriculture and farming. Nitrogen in atmospheric wet deposition can be found in the form of nitrate (NO_3^-) and ammonium (NH_4^+).

Nitrogen compounds have significant effects on forest ecosystems: They are important plant nutrients but in excess may lead to ecosystem eutrophication; they strongly influence plant metabolism (e.g. Silva et al. 2015), forest ecosystem processes (e.g. Meunier et al. 2016), and biodiversity (e.g. Bobbink et al. 2010); and they can also act as acidifying compounds (Bobbink and Hettelingh 2011).

In the last century, human activities led to a dramatic increase in the deposition of nitrogen and sulphur compounds but emission and deposition of sulphur and to a lesser extent nitrogen have significantly decreased in the last decades (Waldner et al. 2014; EEA 2016; Rogora et al. 2016, 2022) due to successful air pollution abatement under the UNECE Air Convention.

Materials and methods

Atmospheric deposition is collected on the ICP Forests Level II intensive monitoring plots under the tree canopy (throughfall samplers, Fig. 6-1, left and center), along tree trunks in beech stands (stemflow sampler, Fig. 6-1, right), and in a nearby clearance (open field samplers). Throughfall samples are used to estimate wet deposition, which is the amount of pollutants carried in by rain and snow, but they also include dry deposition from particulate matter and gases collected by the canopy and having been washed-off. The total deposition to a forest, however, also includes nitrogen taken up by leaves and organic nitrogen compounds. Its input can be estimated by applying canopy and stomata exchange models.

Figure 6-1: Snow samplers (left) and throughfall sampling gutter system (center) in a Level II plot with Norway spruce and stemflow sampler (right) in a European beech plot near Žďár nad Sázavou, Czechia. Images: Arne Verstraeten

It is important to note the different behaviour of individual ions when they interact with the canopy: In the case of sodium (Na^+) and chloride (Cl^-), the interaction is almost negligible, and it can be assumed that their throughfall and stemflow deposition equals the sum of wet and dry deposition. For sulphate, small amounts (< 0.8 kg ha^{-1} y^{-1}) are reported to be taken up by the canopy in areas with very low sulphate deposition, such as northern Sweden (Pihl Karlsson et al. 2024).

Other ions, such as ammonium, are strongly affected by tree canopies and their associated microbial communities. For example, tree leaves can take up ammonium ions and release potassium (K^+) ions and organic compounds, thereby changing the composition of throughfall deposition. Biochemical conversion (e.g. nitrification) is also common (Guerrieri et al. 2024).

Sampling, analysis, and quality control procedures are harmonized on the basis of the ICP Forests Manual (Clarke et al. 2022). Quality control and assurance include laboratory ring-tests, the use of control charts, and conductivity and ion balance checks on all samples (König et al. 2016). In calculating the ion balance, the charge of organic compounds was considered proportional to the dissolved organic carbon (DOC) content following Mosello et al. (2005, 2008).

In this report, we present the results of the 2023 annual throughfall deposition sampling from 288 permanent Level II intensive monitoring plots, collected following the ICP Forests Manual. Ten plots were excluded because the duration of sampling covered less than 90% (329 days) of the year and 60 other plots were marked as "not validated" because the conductivity check was passed for less than 30% of the analyses of the year. Further data were excluded because the laboratory did not participate in the mandatory Working Ring Test (18 plots), or did not pass the minimum requirement of the test for a specific variable: 9 plots for ammonium, 11 for total nitrogen, and 4 for sulphate and chloride.

As the deposition of marine aerosol represents an important contribution to the total deposition of sulphate, calcium, and magnesium, a sea-salt correction was applied, subtracting from the deposition fluxes the marine contribution, calculated as a fraction of the chloride deposition according to the ICP Integrated Monitoring Manual (FEI 2013).

The color classes on the presented maps (low, medium, high) have been chosen to visualize the spatial distribution of deposition rates across Europe and do not necessarily correspond to the ecological impact of the deposition.

Results

The uneven distribution of emission sources and receptors and the complex orography of Europe result in a marked spatial variability of atmospheric deposition. However, on a broader scale, regional patterns in deposition become apparent. In the case of nitrate and ammonium, high and moderate throughfall deposition was found all across Europe, except for northern and north-eastern countries, but mainly in central Europe (Figs. 6-2, 6-3).

Negative effects of nitrogen deposition on forests can become evident when total inorganic deposition of nitrogen exceeds a specific threshold, known as the critical load. Critical loads can be defined for each forest site by modeling, but more generic critical loads (empirical critical loads) are also being used, ranging between 3 and 17 kg N ha^{-1} y^{-1}, depending on forest type and ecosystem compartment (Bobbink et al. 2022). In the forest canopy, a part of the deposited nitrogen may be taken up by leaves and microorganisms in the phyllosphere, transformed into organic nitrogen, or even released. For this reason, throughfall nitrogen deposition is only a rough estimate of the actual deposition reaching the forest floor, but its geographical distribution can be used to estimate the deposition patterns over large areas.

In 2023, throughfall deposition of inorganic and organic nitrogen higher than 10 kg ha^{-1} y^{-1} was mainly measured in most of central Europe, including Germany, Czechia, Poland, Slovakia, Switzerland, Slovenia, but also in the UK, Spain, Belgium, Romania, and Italy (Fig. 6-4).

Throughfall deposition of sulphate (corrected for the marine contribution) was relatively low in most of Europe. The highest values were found at a small number of sites in Austria, Czechia, Hungary, and Greece (Fig. 6-5).

Calcium and magnesium are also analyzed in the ICP Forests deposition monitoring network as their deposition can buffer the acidifying effects of atmospheric deposition and protect the soil from acidification. High values of (sea-salt corrected) calcium and/or magnesium throughfall deposition were mostly recorded in the Mediterranean region (Spain, France, Italy, Greece) extending north and east to Belgium, Switzerland, Austria, Slovenia, Romania, and a few plots in Denmark, Germany, Poland, and Hungary (Figs. 6-6, 6-7).

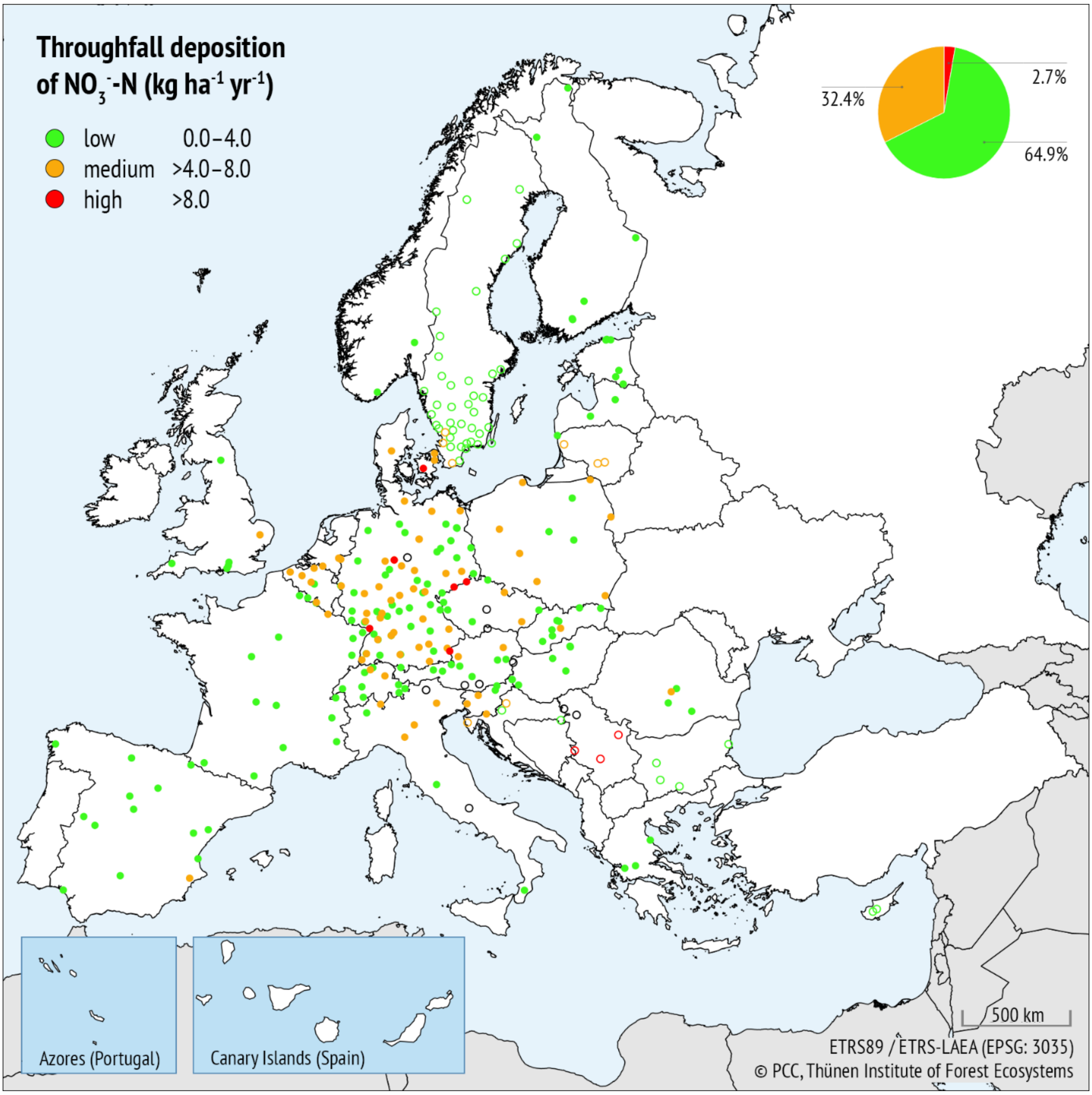

Figure 6-2: Throughfall deposition of nitrate-nitrogen (kg NO_3^--N ha^{-1} yr^{-1}) measured in 2023 on the ICP Forests Level II plots and the Swedish Throughfall Monitoring Network. Colored dots: validated data. Colored circles: not validated data. Black circles: monitoring period shorter than 330 days or irregular sampling. The pie chart shows the percentage of plots with low, medium, and high deposition for validated data only.

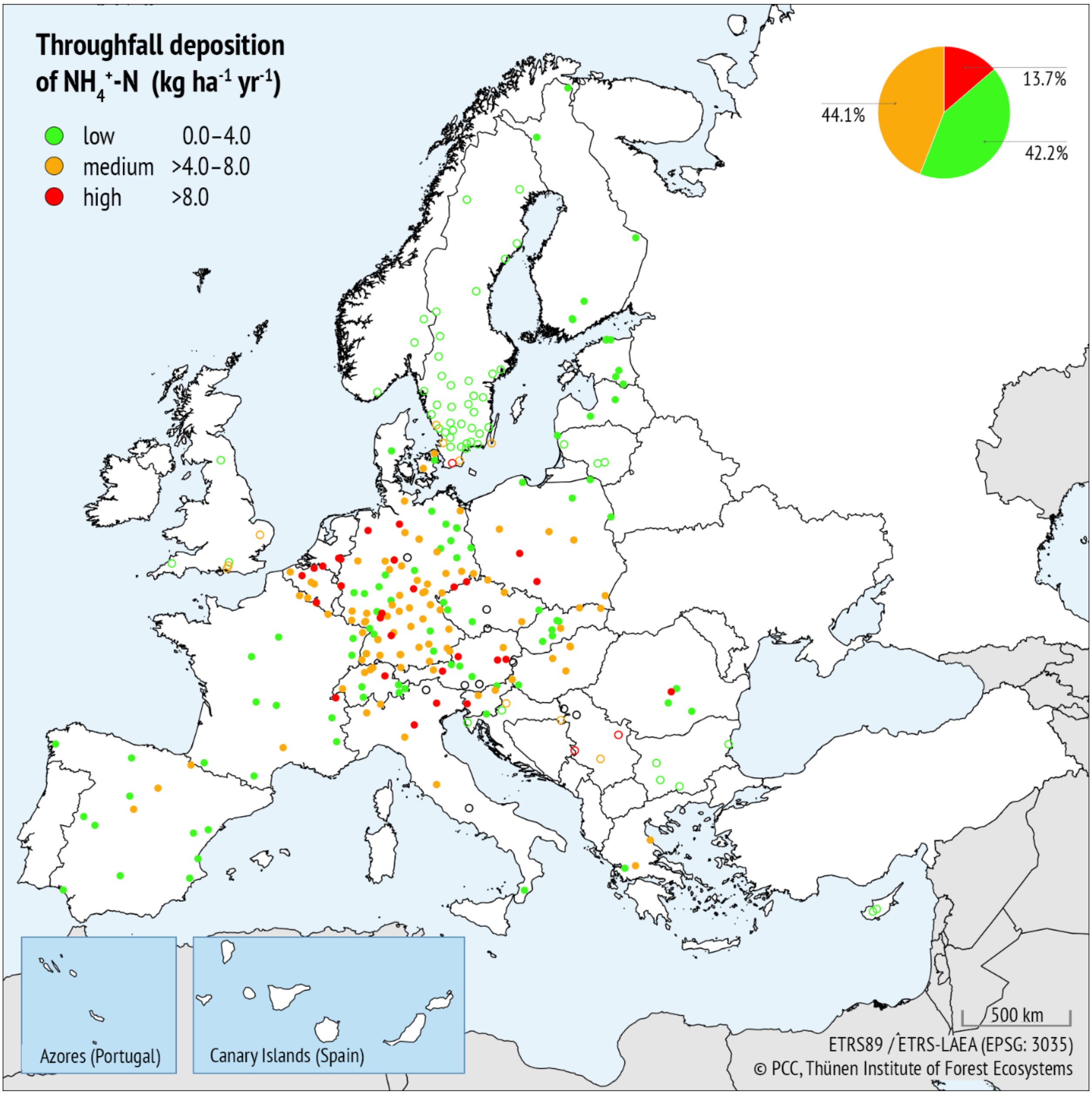

Figure 6-3: Throughfall deposition of ammonium-nitrogen (kg NH_4^+-N ha^{-1} yr^{-1}) measured in 2023 on the ICP Forests Level II plots and the Swedish Throughfall Monitoring Network. Colored dots: validated data. Colored circles: not validated data. Black circles: monitoring period shorter than 330 days or irregular sampling. The pie chart shows the percentage of plots with low, medium, and high deposition for validated data only.

EVALUATIONS

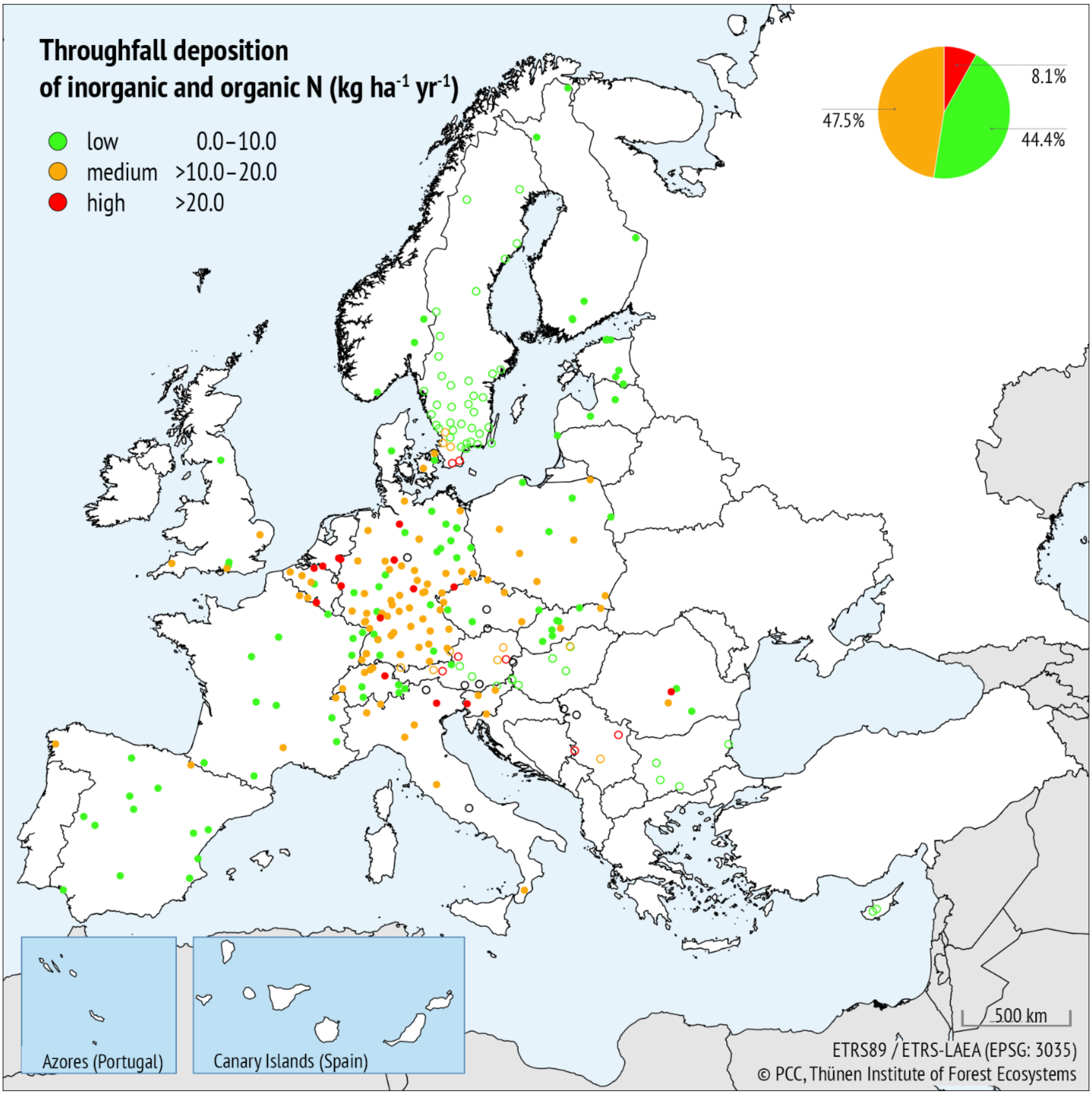

Figure 6-4: Throughfall deposition of the sum of inorganic and organic nitrogen (kg ha^{-1} yr^{-1}) measured in 2023 on the ICP Forests Level II plots and the Swedish Throughfall Monitoring Network. Colored dots: validated data. Colored circles: not validated data. Black circles: monitoring period shorter than 330 days or irregular sampling. The pie chart shows the percentage of plots with low, medium, and high deposition for validated data only.

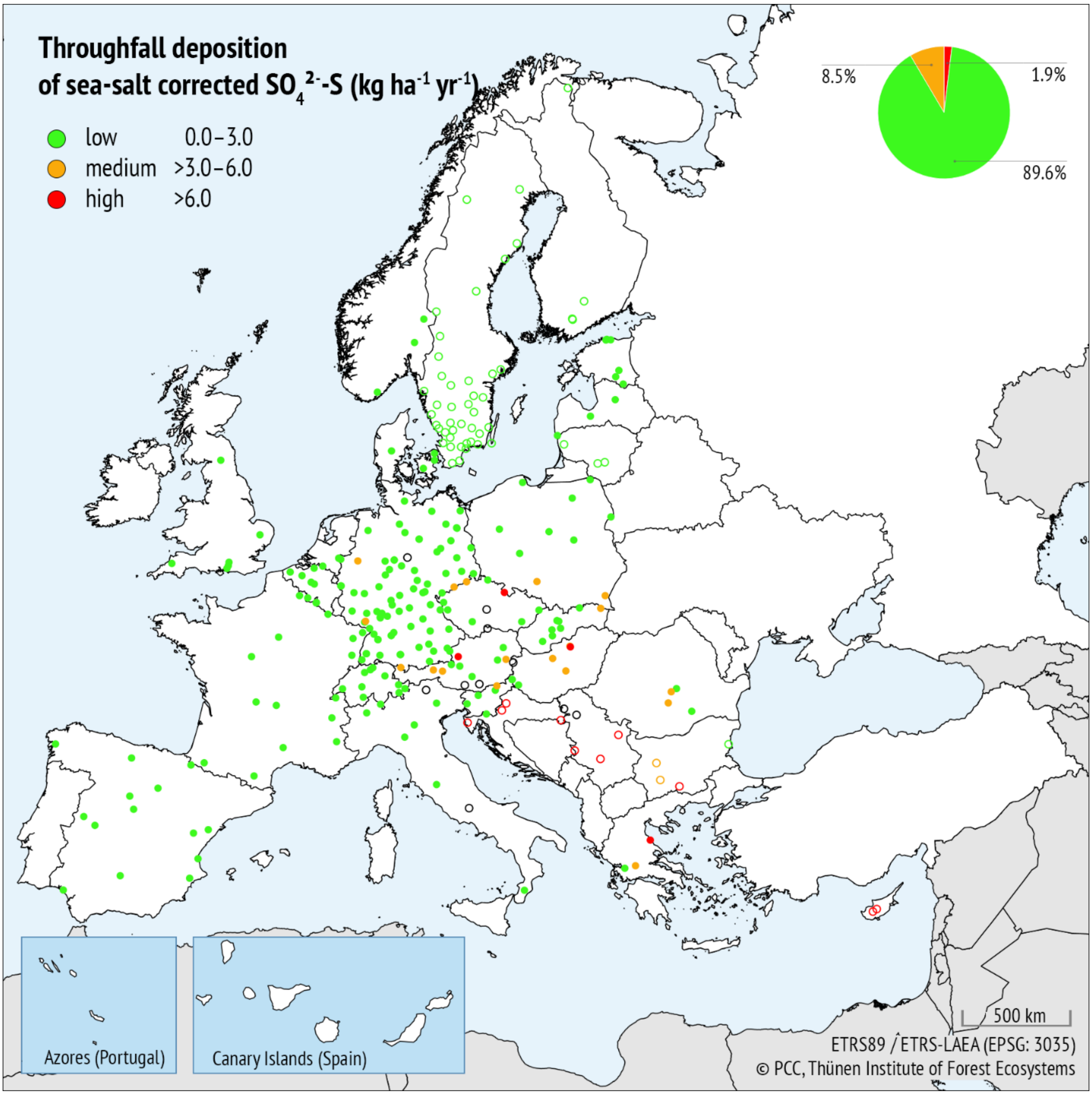

Figure 6-5: Throughfall deposition of sea-salt corrected sulphate-sulphur (kg SO_4^{2-}-S ha^{-1} yr^{-1}) measured in 2023 on the ICP Forests Level II plots and the Swedish Throughfall Monitoring Network. Colored dots: validated data. Colored circles: not validated data. Black circles: monitoring period shorter than 330 days or irregular sampling. The pie chart shows the percentage of plots with low, medium, and high deposition for validated data only.

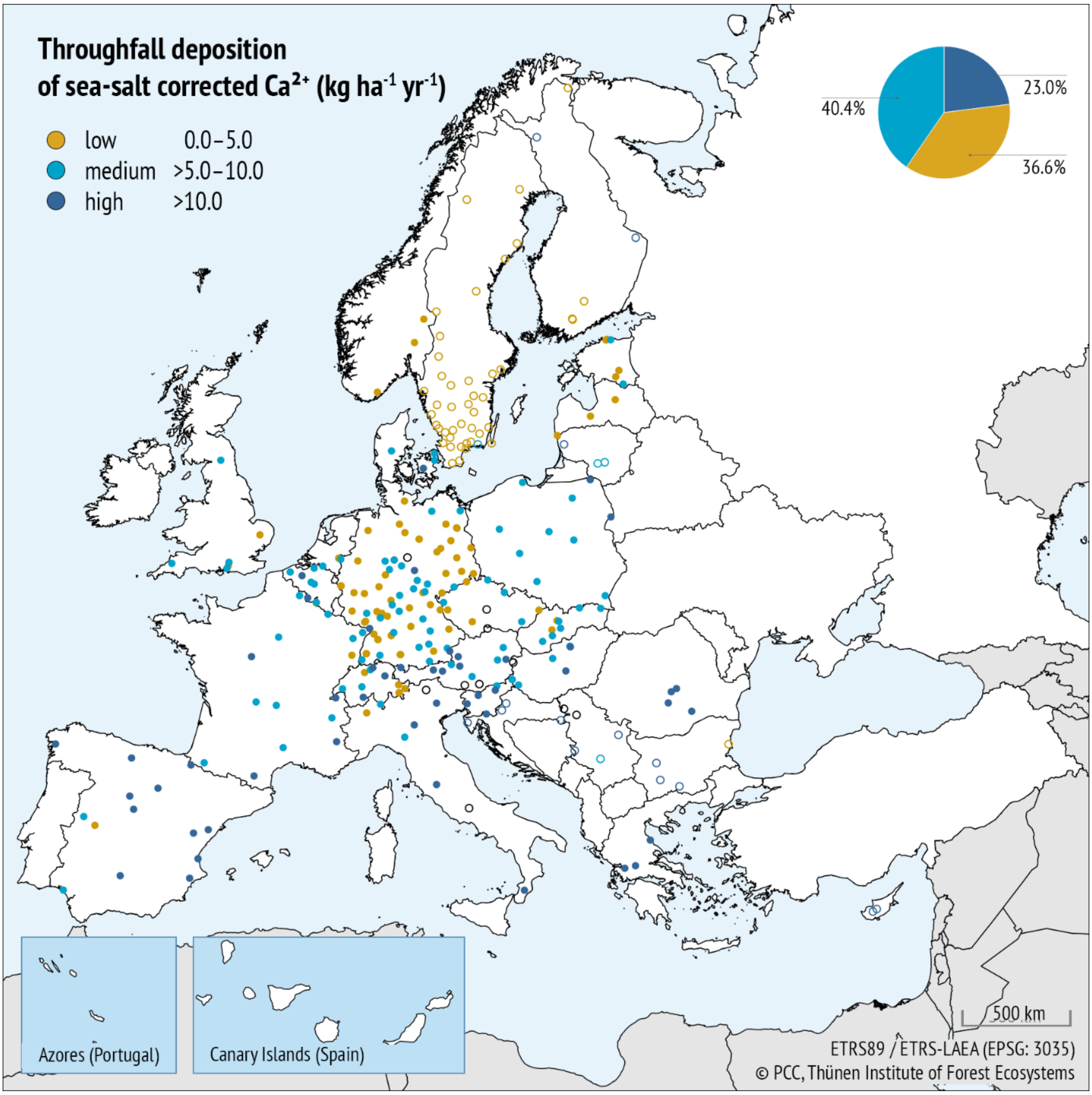

Figure 6-6: Throughfall deposition of sea-salt corrected calcium (kg Ca^{2+} ha^{-1} yr^{-1}) measured in 2023 on the ICP Forests Level II plots and the Swedish Throughfall Monitoring Network. Colored dots: validated data. Colored circles: not validated data. Black circles: monitoring period shorter than 330 days or irregular sampling. The pie chart shows the percentage of plots with low, medium, and high deposition for validated data only.

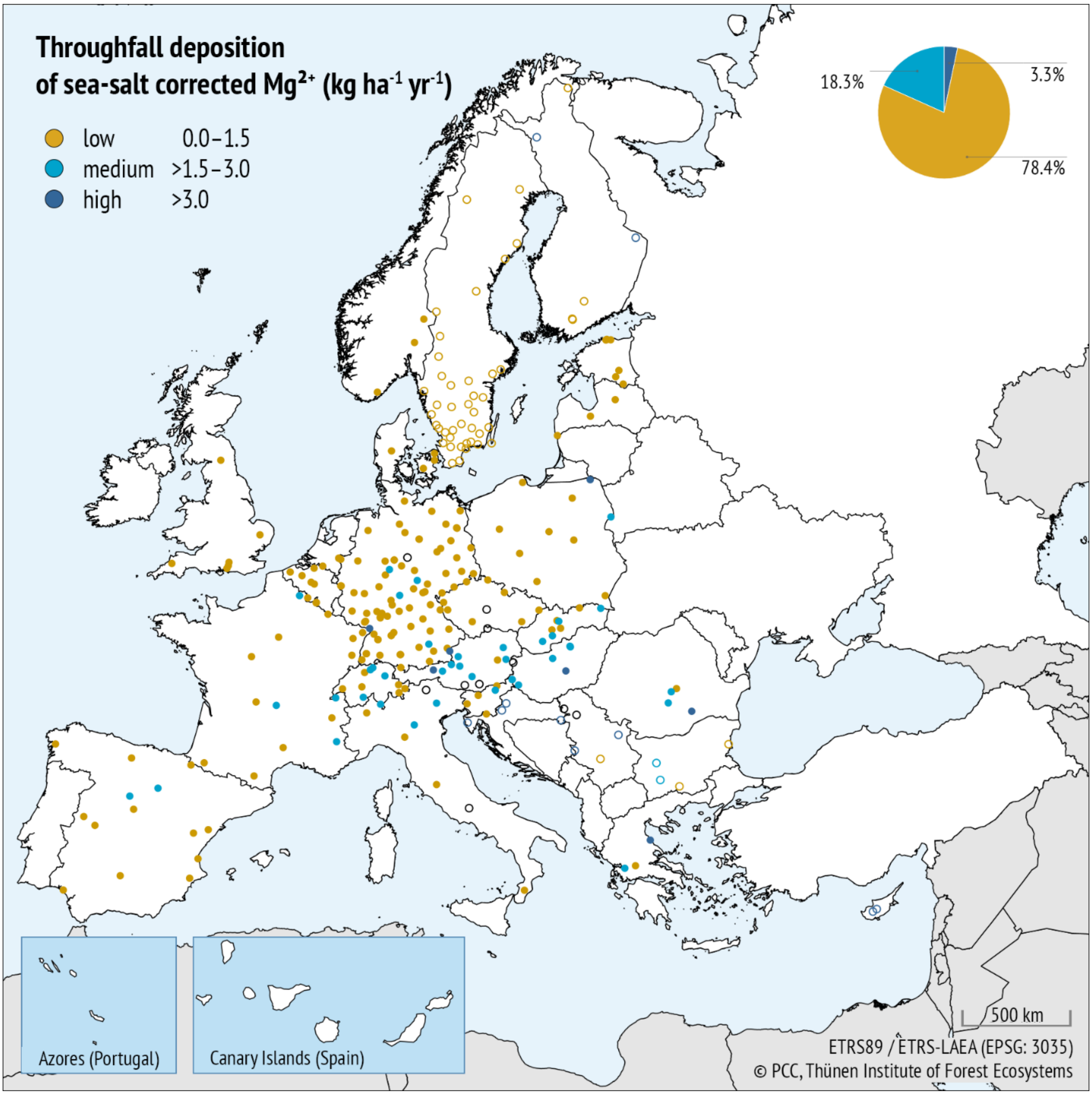

Figure 6-7: Throughfall deposition of sea-salt corrected magnesium (kg Mg^{2+} ha^{-1} yr^{-1}) measured in 2023 on the ICP Forests Level II plots and the Swedish Throughfall Monitoring Network. Colored dots: validated data. Colored circles: not validated data. Black circles: monitoring period shorter than 330 days or irregular sampling. The pie chart shows the percentage of plots with low, medium, and high deposition for validated data only.

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