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ATMOSPHERIC DEPOSITION IN EUROPEAN FORESTS IN 2022

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Introduction

The atmosphere contains a large number of substances of natural and anthropogenic origin. A large part of these can settle, be adsorbed to receptor surfaces, or be included in rain and snow and finally reach land surface as wet and dry deposition.

Sulphur deposition almost completely occurs 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 derive mainly from coal combustion, but also from vehicle fuel combustion, volcanoes, forest fires, and other sources, and have increased since the 1850s, causing an increase in sulphate deposition and deposition acidity, which can only partly be 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 nitrogen oxides (NO_x) during lightning. However, human activities cause high emissions of NO_x during combustion processes, and of ammonia (NH_3) from agriculture and farming. Nitrogen 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 that - when in excess - may lead to ecosystem eutrophication, and 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 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), along tree trunks in beech stands (stemflow samplers, 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 exchange models.

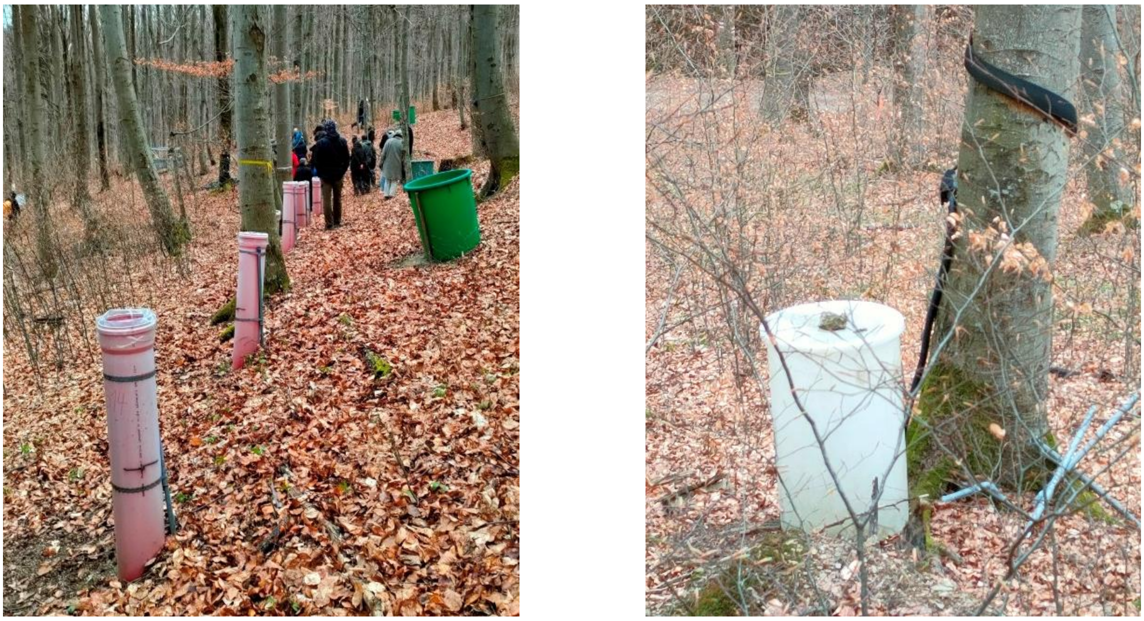

Figure 6-1: Throughfall samplers (left) and stemflow sampler (right) on Level II plot 'Klausen-Leopoldsdorf' in European beech (*Fagus sylvatica*) stand located west of Vienna, Austria. Images: Arne Verstraeten

It is important to note the different behaviour of individual ions when they interact with the canopy: in the case of sodium (Na^+), chloride (Cl^-), and sulphate, the interaction is almost negligible and it can be assumed that their throughfall deposition equals the sum of wet and dry deposition. This is not the case for other ions, such as ammonium: Tree canopies and their associated microbial communities strongly interact with them. For example, tree leaves can take up ammonium ions and release potassium (K^+) ions and organic compounds, thereby changing the composition of throughfall deposition.

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 2022 annual throughfall deposition sampling from 281 permanent Level II intensive monitoring plots, following the ICP Forests Manual. Fourteen plots were excluded because the duration of sampling covered less than 90% (329 days) of the year, and 86 other plots were marked as ”not validated” because the conductivity check was passed for less than 30% of the analyses of the year, or the laboratory did not participate in the mandatory Working Ring Test, or did not pass the minimum requirement of the test. For further 4 sites, data for magnesium were rejected because the laboratory did not pass the test for that variable. The same applies to one site for ammonium.

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 heterogeneous spatial distribution of emission sources and receptors and the complex orography of parts of Europe result in a marked spatial variability of atmospheric deposition. However, on a broader scale, regional patterns in deposition arise.

In the case of nitrate and ammonium, high and moderate throughfall deposition was mainly found in central Europe, from Belgium to Germany to Poland, extending southward to Switzerland, Austria, Italy, and Slovenia, but some plots with high deposition were also reported from other countries (Figs. 6-2, 6-3).

Negative effects of nitrogen deposition on forests can become evident when inorganic nitrogen deposition (i.e. the sum of nitrate and ammonium deposition) 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 2022, throughfall inorganic nitrogen deposition higher than 10 kg ha^{-1} y^{-1} was mainly measured in central Europe, including Belgium, Germany, Poland, Czechia, Austria, Switzerland, Slovenia and northern Italy (Fig. 6-4), but high deposition was also found in other countries, like France, the UK, Denmark, Sweden, Serbia, Greece, and Cyprus. Because total nitrogen deposition on forests is higher than throughfall nitrogen deposition (Braun et al. 2022), the critical loads for nitrogen are likely still exceeded in a large part of Europe.

Sulphate deposition has substantially decreased since the start of the monitoring in some countries as early as in 1985 but high throughfall sulphate deposition is still found close to large point sources. In southern Europe, sulphate deposition is also influenced by volcanic emission and by the episodic deposition of Saharan dust. In 2022, high and moderate throughfall deposition of sulphate (corrected for the marine contribution) was found mainly in central and south-eastern Europe with a small number of sites in Germany, Poland, Czechia, Slovakia, Croatia, Serbia, Bulgaria, Greece, and Cyprus (Fig. 6-5).

Although not considered atmospheric pollutants, calcium and magnesium are also analyzed in the ICP Forests deposition monitoring network, as their deposition can buffer the acidifying effect of atmospheric deposition and protect soil from acidification. High (sea-salt corrected) calcium throughfall deposition was mostly reported from a large area in central and southern Europe (Fig. 6-6). High magnesium deposition was found all across Europe (Fig. 6-7).

Deposition trends in European forests over time

Atmospheric deposition of nitrogen and sulphur compounds markedly decreased in the last years, yet at different rates. Considering 133 plots for which deposition values were validated for the whole period 2017–2022, throughfall deposition of oxidized nitrogen, reduced nitrogen and non-marine sulphur in 2020–2022 was lower than in 2017–2019 by 24%, 12% and 31%, respectively (Fig. 6-8, left panel), while the differences in the amount of precipitation between the two periods were negligible.

In a subset of 49 plots mainly located in central and eastern Europe (shown in red in Fig, 6-8, central panel), a strong decrease in oxidized nitrogen deposition was recorded between 2019 and 2020, probably partly because of the reduction in nitrogen oxide emission during the COVID-19 pandemic lockdown. In those plots, oxidized nitrogen deposition increased again in 2021 and 2022, without reaching the level of the 2017–2019 period (Fig. 6-8, right panel).

Conclusions

Sulphate throughfall deposition has substantially decreased since the start of the monitoring nearly 40 years ago and today high sulphate deposition is mainly restricted to areas close to large point sources and in central and south-eastern Europe. High throughfall deposition of inorganic nitrogen is still observed throughout central Europe, with high ammonium deposition having been measured in a wider area than nitrate. A significant decrease in nitrogen emission across Europe was detected in 2019-2020 and might be associated with the COVID-19 pandemic lockdown.

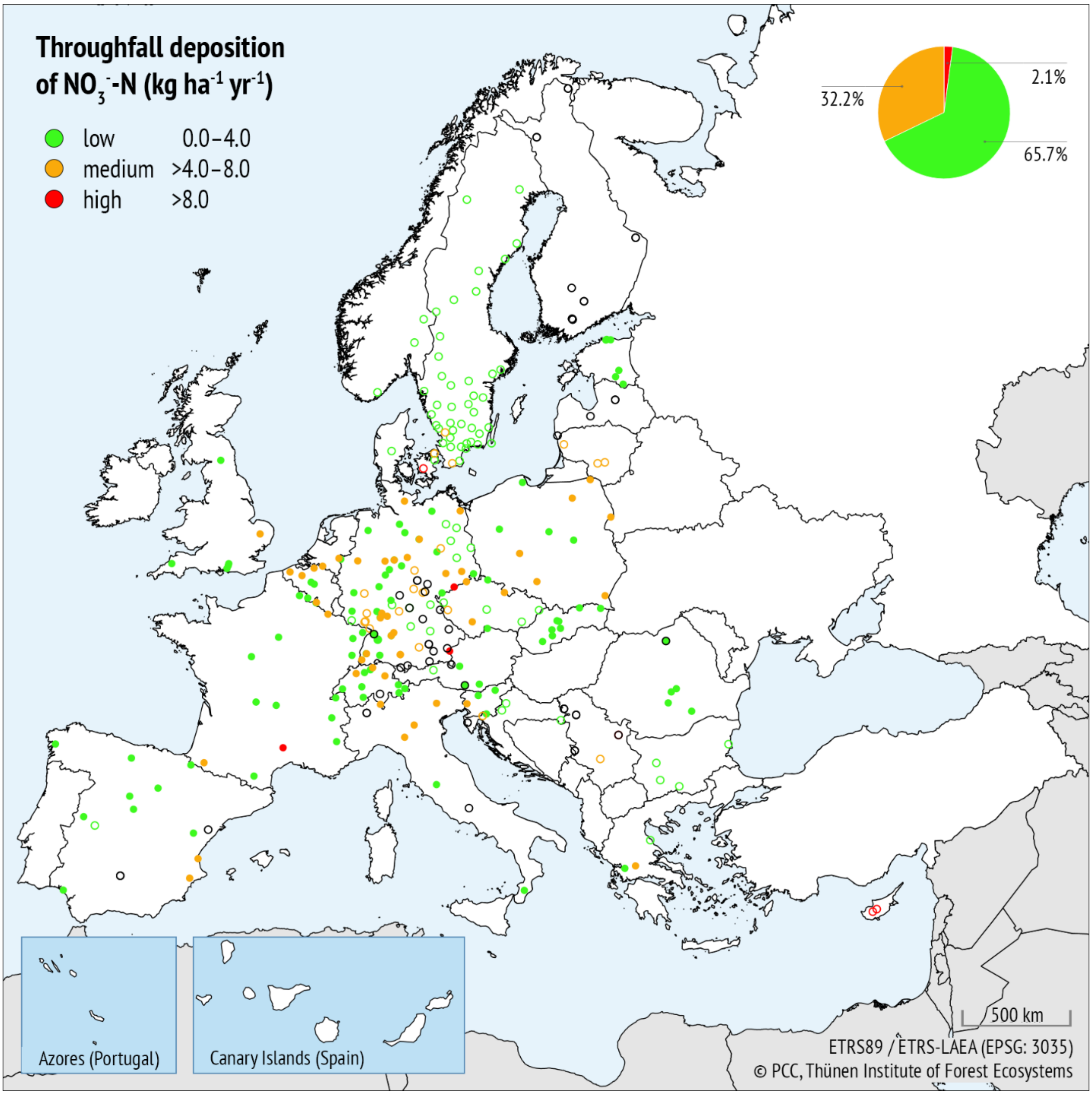

Figure 6-2: Throughfall deposition of nitrate-nitrogen (kg NO_3^--N ha^{-1} yr^{-1}) measured in 2022 on the ICP Forests Level II plots and the Swedish Throughfall Monitoring Network. Colored dots: validated data. Colored circles: not validated data. Black circles: monitoring period shorter than 330 days or irregular sampling. The pie chart shows the percentage of plots with low, medium, and high deposition for validated data only.

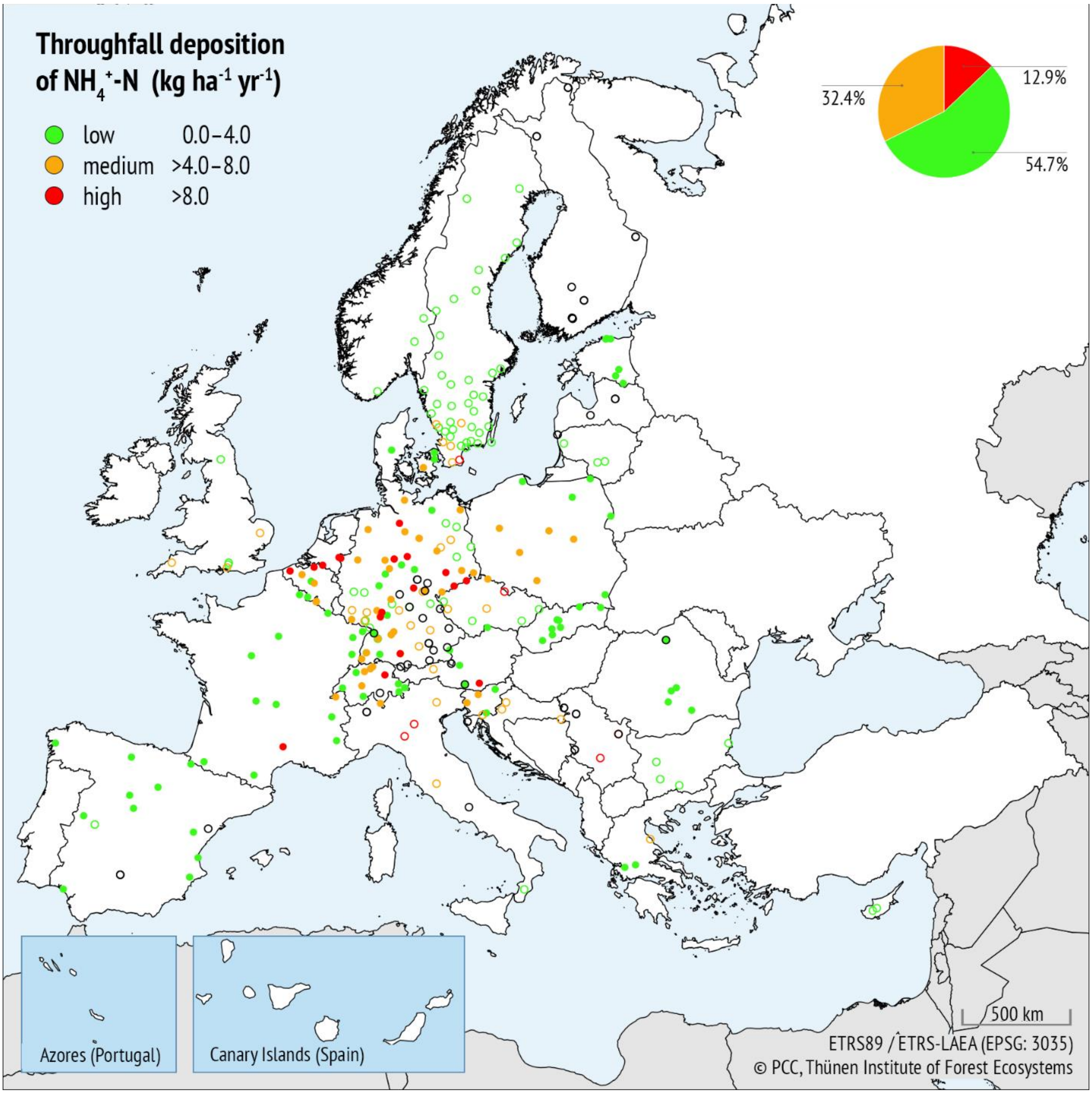

Figure 6-3: Throughfall deposition of ammonium-nitrogen (kg NH_4^+-N ha^{-1} yr^{-1}) measured in 2022 on the ICP Forests Level II plots and the Swedish Throughfall Monitoring Network. Colored dots: validated data. Colored circles: not validated data. Black circles: monitoring period shorter than 330 days or irregular sampling. The pie chart shows the percentage of plots with low, medium, and high deposition for validated data only.

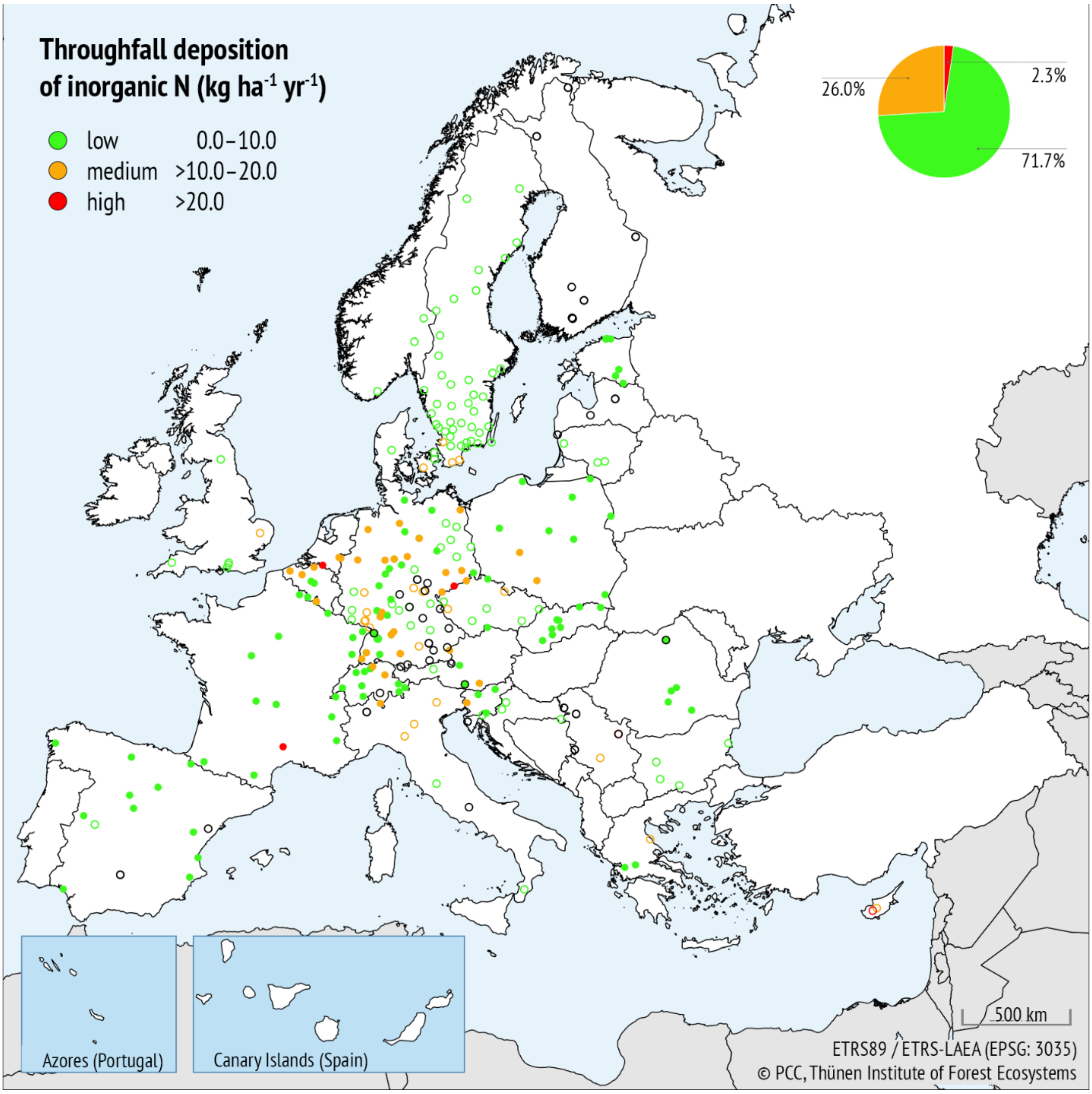

Figure 6-4: Throughfall deposition of inorganic nitrogen (kg NO$_3^-$-N + NH$_4^+$-N ha^{-1} yr^{-1}) measured in 2022 on the ICP Forests Level II plots and the Swedish Throughfall Monitoring Network. Colored dots: validated data. Colored circles: not validated data. Black circles: monitoring period 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.

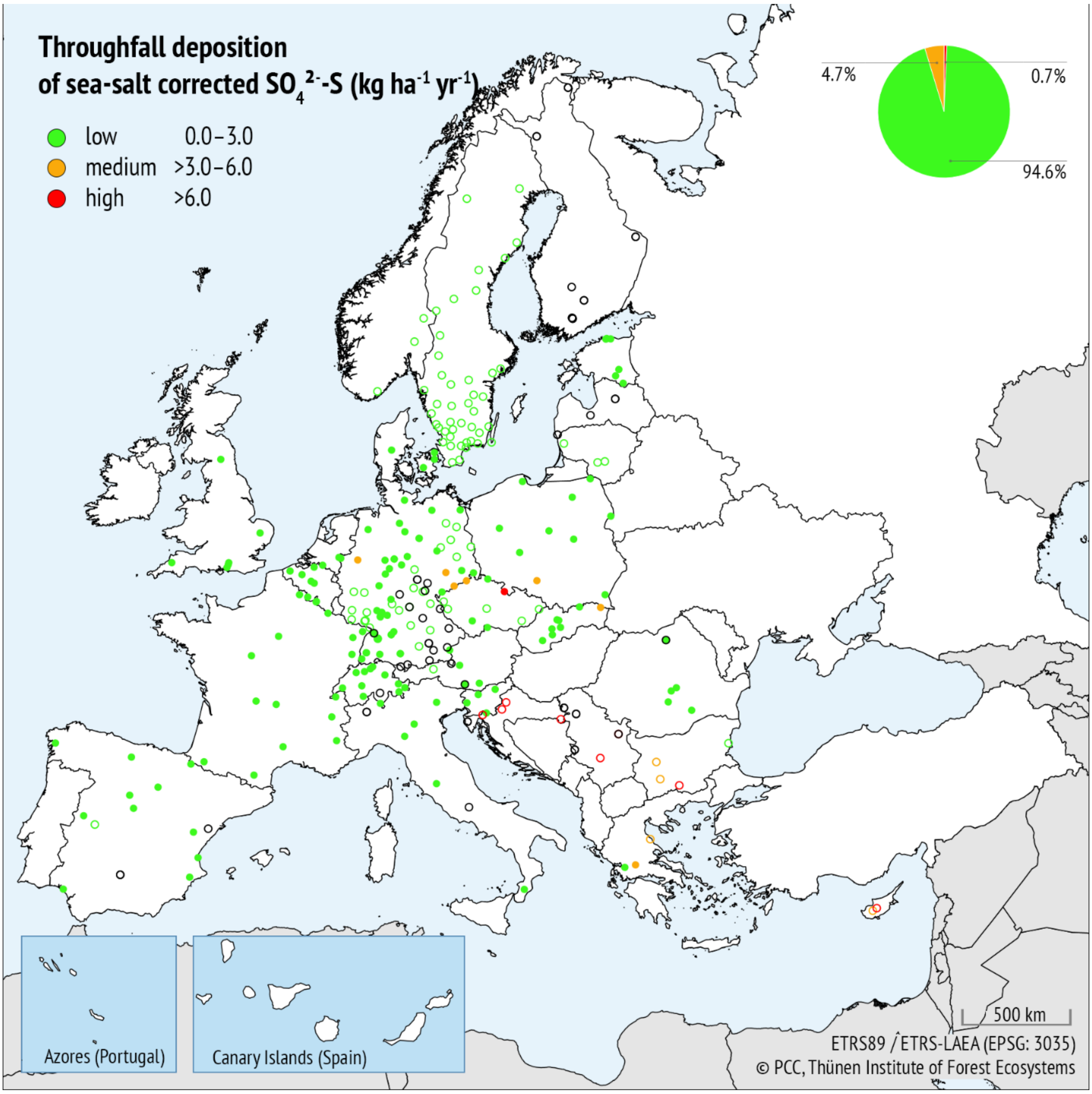

Figure 6-5: Throughfall deposition of sea-salt corrected sulphate-sulphur (kg SO_4^{2-}-S ha^{-1} yr^{-1}) measured in 2022 on the ICP Forests Level II plots and the Swedish Throughfall Monitoring Network. Colored dots: validated data. Colored circles: not validated data. Black circles: monitoring period 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.

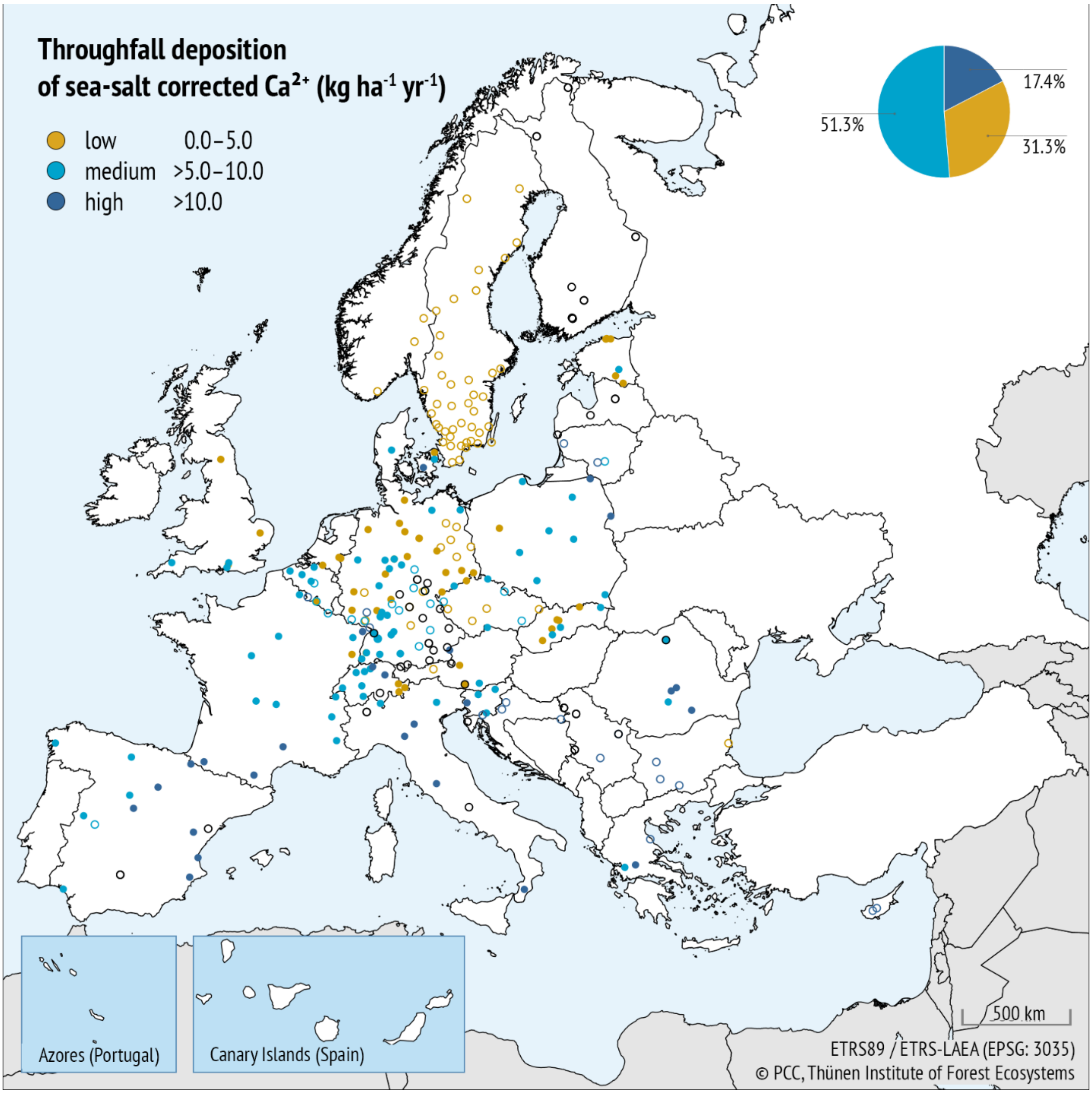

Figure 6-6: Throughfall deposition of sea-salt corrected calcium (kg Ca^{2+} ha^{-1} yr^{-1}) measured in 2022 on the ICP Forests Level II plots and the Swedish Throughfall Monitoring Network. Colored dots: validated data. Colored circles: not validated data. Black circles: monitoring period shorter than 330 days or irregular sampling. The pie chart shows the percentage of plots with low, medium, and high deposition for validated data only.

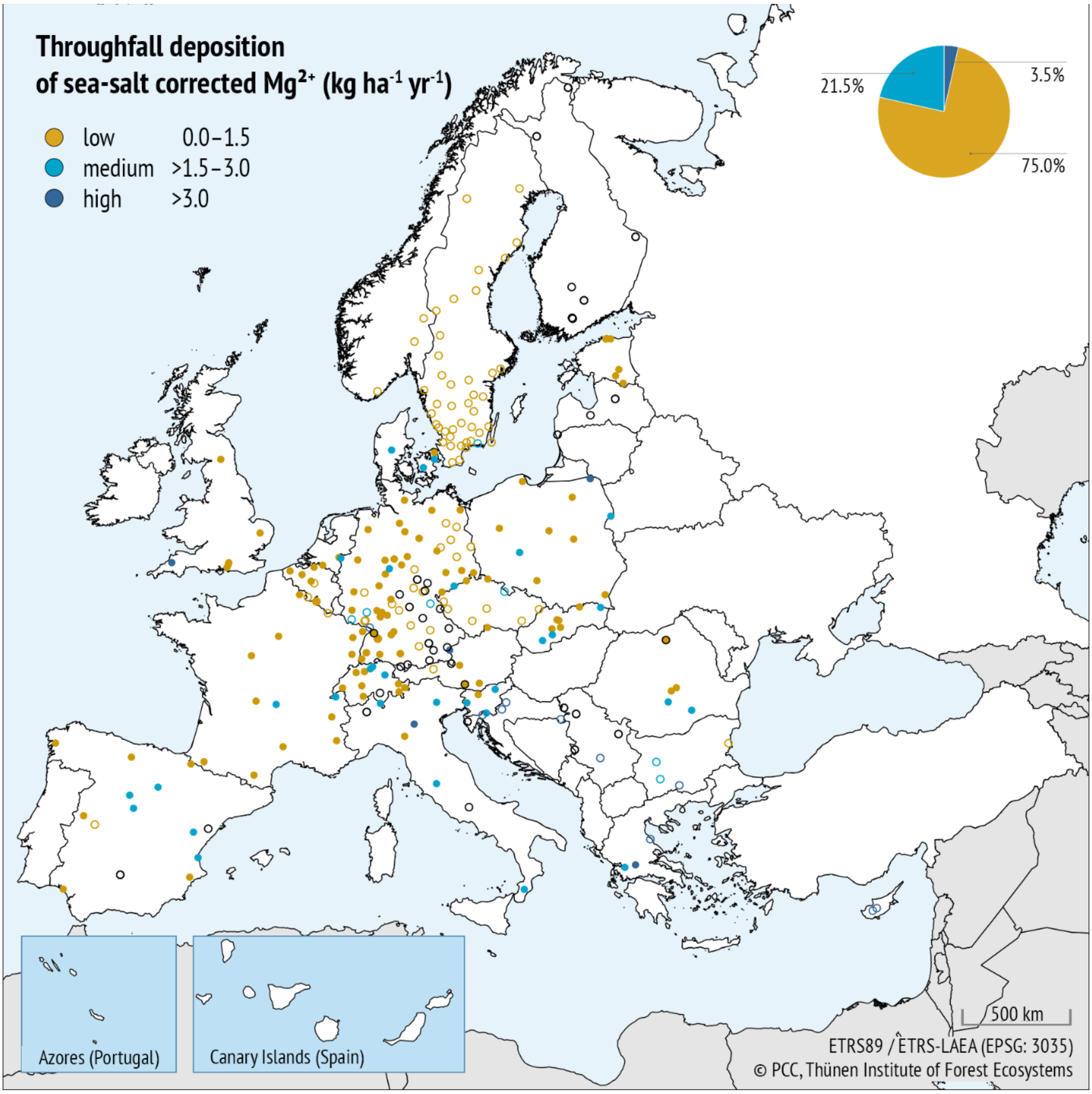

Figure 6-7: Throughfall deposition of sea-salt corrected magnesium (kg Mg^{2+} ha^{-1} yr^{-1}) measured in 2022 on the ICP Forests Level II plots and the Swedish Throughfall Monitoring Network. Colored dots: validated data. Colored circles: not validated data. Black circles: monitoring period shorter than 330 days or irregular sampling. The pie chart shows the percentage of plots with low, medium, and high deposition for validated data only.

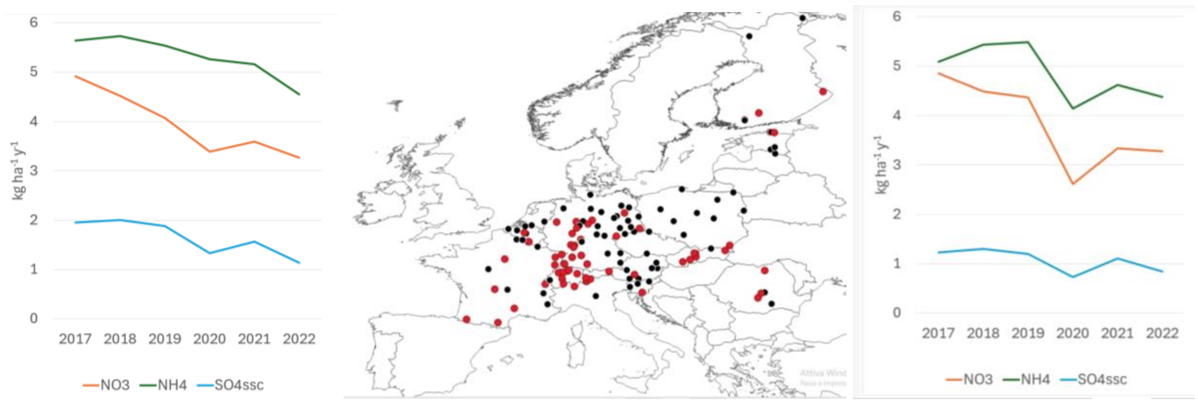

Figure 6-8: Average throughfall deposition of nitrogen and sulphur compounds (left panel) in 133 plots for which deposition values were validated for the whole period 2017–2022 (map in the central panel). The right panel shows the average values for a subset of 49 plots (marked in red in the central panel) in which oxidized nitrogen deposition dropped by more than 25% between 2019 and 2020 (right panel).

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