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Forest soils further acidify in core Natura 2000 areas amongst unaware government policy

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ABSTRACT

The intensification of agriculture and livestock husbandry has led to increasing atmospheric deposition of nitrogenous compounds and soil acidification. We field measured extremely acidic soils with pH < 3 (i.e., soils with the acidity of domestic vinegar) over extensive areas of the forested national parks on sandy soils in the Netherlands. These areas show stress from the negative impacts of increased soil acidity on forest health and biodiversity. We demonstrate that soil acidity has worsened from an average pH of approximately 4.5 to the current average pH = 3.2 over the last 22 years for extensive areas of Natura 2000 forest soils in the Netherlands. Current government policy has been guided without knowledge of such extreme acidity because the field data sampling does not cover Natura 2000 areas, and soil acidification was estimated based on poorly calibrated atmospheric nitrogen deposition models. The policy challenge of soil acidification in Natura2000 areas is solvable with the following recommendations:

- Implement regulatory action to biennially field sample soil pH across Natura 2000 forest parks, focusing on sandy soils with limited buffering capacity.
- To include in models of nitrogen deposition all sources of nitrogen, including for example off-leash dog walking areas in Natura 2000 forest areas.
- To use these soil pH field samples to regularly recalibrate estimates of soil pH from atmospheric nitrogen deposition models to better inform government, industry, and the agricultural sector about the ongoing impact of N deposition on already severely acidic soils.
- To implement further significant reductions in the deposition of all nitrogen compounds on Natura 2000 areas.

1. Background

Soil acidification caused by atmospheric deposition from industrial nitrogen emissions was considered largely solved in the 2000s, thanks to regulations requiring flue gas treatment (e.g., smokestack scrubbers) (Basu, 2007) from power stations, factories, and vehicles burning fossil fuels. Difficult but pivotal political decisions were made to reduce the negative impacts of the industrial pollution, by balancing intensive lobbying from industry against evidence of large-scale forest die-back and ecosystem decline (EEA, 2014), with many countries, including the EU, enacting stringent legislation to limit emissions.

Despite this decisive action by the EU and its Member States which stopped and reversed the negative environmental impacts of acid rain, there were unintended consequences. Firstly, the decision accelerated the migration of European manufacturing and industry to countries with fewer environmental controls (Fowler et al., 2020; Xu, 2013), thereby avoiding expenses in developing and installing the equipment necessary to remove polluting emissions from the exhaust flues. Secondly, in a perverse irony, soil acidification is now blighting rapidly developing industrial countries with weaker environmental controls such as China (Lu et al., 2010), where government policy has implemented actions to reverse these trends (Liu et al., 2020; Misselbrook et al., 2022), though as in Europe more fragile areas and sensitive forests with limited soil buffering capacity appear to remain under threat (Qiao et al., 2021;

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Zhang et al., 2023). And thirdly, because the emphasis was on transport and industrial pollution (Fowler et al., 2020), the nitrogen emissions from farms benefitted from less stringent deadlines for reduction.

In a scenario reminiscent of the 1980s and 1990s, forest soils, which never fully recovered from the 'industrial acid rain', are again acidifying due to nitrogen deposition. For the extensive areas of glacial deposited sandy soils across NW Europe, for example in the Netherlands, Natura 2000 areas are particularly impacted by volatized manure emitted by adjacent farms (CBS, 2022). Forecasts by the European Environment Agency (EEA) (EEA, 2022) show almost all EU member states will not reach emission reduction targets by 2030, with farmers being responsible for more than 90 % of reactive nitrogen in the form of ammonia (NH3) (EEA, 2020) which is an important source of ongoing soil acidification (Kopácek & Posch, 2011). The acidification accelerates once the soil base cations are depleted releasing aluminum, with the ongoing acidification (under continuing nitrogen deposition) increasing iron concentrations. In this process, plant biomass is reduced as shoot calcium and magnesium concentrations decrease and the concentration of toxic aluminum increases (Bowman et al., 2008), along with decreasing soil and vegetation biodiversity (Azevedo et al., 2013; Zhang et al., 2018).

The EU has repeatedly allowed Member States to exceed atmospheric nitrogen emission levels. But concerned citizens and other agencies have won recent court cases, for example in the Netherlands (Wikipedia, 2023), forcing government to meet nitrogen emission levels regulated under EU and Dutch law. These further Dutch restrictions to reduce nitrogen emissions, introduced in 2021, included limiting vehicle speeds nationally to 100 km/h, curtailing large building projects, and reducing emissions by farmers. Of these three main sources of nitrogen emissions, agriculture represents the largest component of 70 % in the Netherlands, or approximately 178 kiloton NO_x and 120 kiloton NH_3 in 2021 (CBS, 2022, 2023). There has been a continuing political reluctance in the Netherlands and other EU Member States to tackle the issue of nitrogen emissions from farms, due to effective lobbying from this sector to minimize the impact on their businesses from further regulations emission controls and enforcement, and the importance to the Dutch economy of agricultural and food trade highlighted by a trade surplus of €34 billion in 2022, with gross exports being €122 billion (WUR, 2023).

Nitrogen deposition creates a wicked problem for policy makers and politicians. As the agricultural sector prospered with government encouragement through R&D, subsidies, tax deductions, and easily obtained bank loans, farmers were actively encouraged to increase livestock numbers and agricultural production through mechanization, and further intensified production. Naturally, this benefitted the EU and Member State economies, and turned some member states including the Netherlands into net agricultural exporters. But in 2022–2023, in response to concrete government proposals to reduce livestock emissions and intensive agriculture, Dutch farmers and their related organizations undertook widespread and extended protests with significant political and societal impact.

2. Mapping nitrogen deposition

The mapping of atmospheric nitrogen deposition provided the scientific evidence for government to restrict nitrogen emissions, with the modelling undertaken at fine to coarse scales with grid cells ranging between 100 m and 1 km (in the Netherlands - Fig. 1a) (CBS, 2022; RIVM, 2023a) and 0.1° (approx. 11.1 km across Europe - Fig. 1b) (Dirnbock et al., 2018). The critical load methodology is a tool to assess risk of air pollution impacts on ecosystems and informs government policy about damage to ecosystems from critical pollutant levels (EEA, 2022). The EU's Air Quality Directive addresses atmospheric nitrogen deposition (NO_x, NH_3) using the critical load concept (EEA, 2022) for sensitive ecosystems such as forests (Forsius et al., 2021). In the Netherlands, Government proposals to reduce the impact of nitrogen deposition from farms targeted those close to nature reserves and

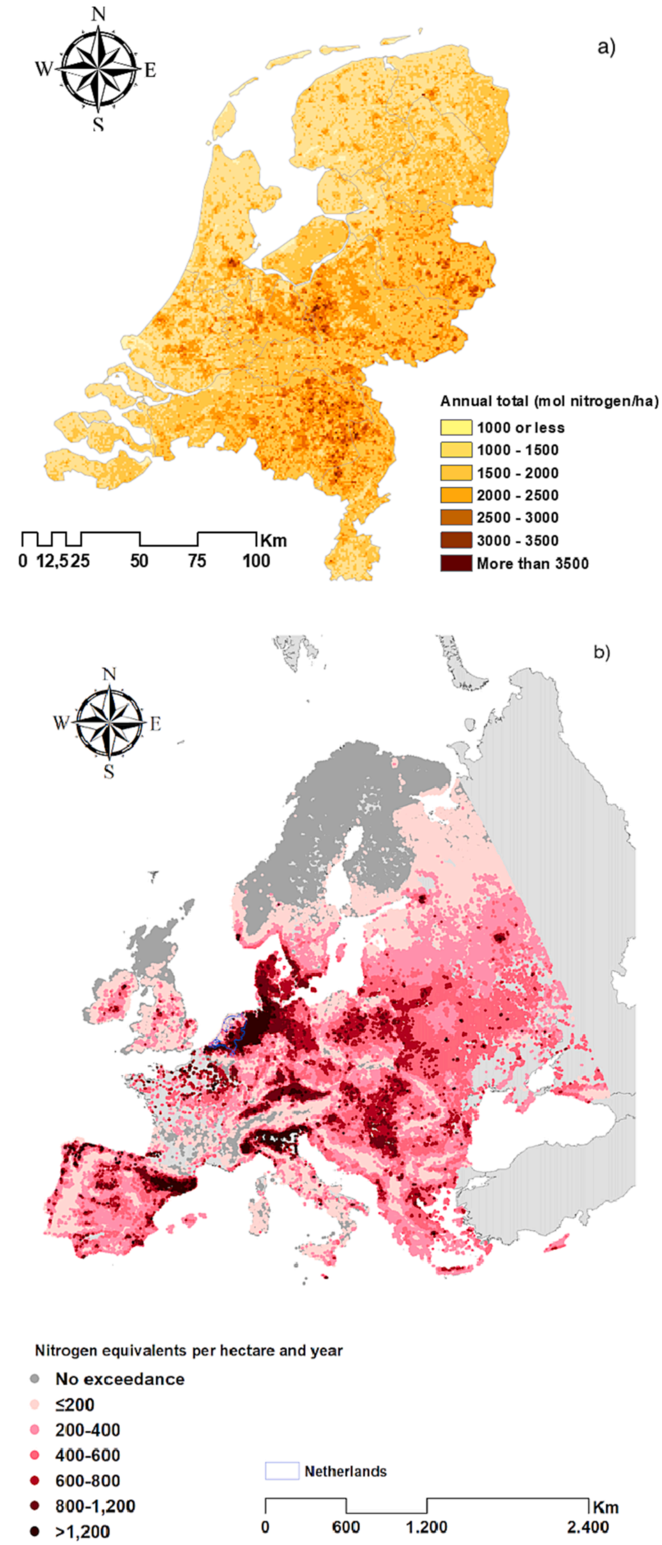

Fig. 1. A) Atmospheric deposition hotspots of nitrogen compounds across the netherlands in 2018 (mol n/ha) (CBS, 2022); b) Exceedance of atmospheric nitrogen deposition above critical loads for eutrophication in Europe in 2020 (N equivalents per ha) (EEA, 2022).

protected by EU Natura 2000 regulations. Emission inventory models show these farms are responsible for ammonia emissions from livestock, manure, and agricultural fertilization, causing soil acidification from nitrogen deposition, with local hotspots of more than 49 kg N/ha being aerially deposited in the central Netherlands (CBS, 2022). These extreme levels can be further substantially exceeded in Natura 2000 areas used for off-leash dog walking, with recent research demonstrating significant additional nitrogen deposition through dog faeces and urine (De Frenne et al., 2022).

Maps informing about rates of deposition of nitrogen compounds across Europe are derived using atmospheric and climate models (Fig. 2) and calibrated and validated using ground metering stations (RIVM, 2023b). In the Netherlands, extensive natural areas of forests and heathlands are especially sensitive to the effects of atmospheric nitrogen deposition because their poor sandy soils of glacial origin lack buffering capacity against acidification. Linking the amount of nitrogen compounds deposited from the atmosphere with soil acidification processes is generally calibrated using vegetation land cover (Rijksoverheid, 2020) instead of direct soil pH field measurements.

3. New evidence of worsening soil acidification in Dutch Natura 2000 areas

To measure actual soil pH levels in the mixed temperate natural forests (comprising deciduous, coniferous and mixed forest types), we established 120 stratified random (by forest type) field plots across the predominantly sandy podzol (moderpodzol and xeropodzol) and limited vague soils (Hartemink & de Bakker, 2002) of the Veluwe region of the central Netherlands, with the pH of each plot being determined by bulk soil collection from 2 soil samples from the top 10 cm being dissolved in ultra-pure water (1:2.5 soil/water ratio), and pH measurement (following a strict quality control procedure using a Metrohm 914 pH and conductivity meter) as well as nitrogen (with soil nitrogen content of samples expressed as %N being determined with a Perkin Elmer 2400 CHN/O Series II analyzer). From these data, we confirmed the most acidic forest soils correlate with increasing soil nitrogen in the forests of the central Netherlands (Fig. 2). We were astonished by the very low pH values of our soil samples measured from field plots in forests managed primarily for conservation and protection of biodiversity (Fig. 2).

Across Europe, the LUCAS soil database (ESDAC, 2023) concatenates field measurements from 2009 (22,000 samples), 2015 (21,859 samples) and 2018 (19,984 samples), from which we extracted soil pH at a 30 m resolution using an inverse distance weighted (IDW) algorithm (top line of maps – Fig. 3). We then clipped maps of soil pH for the Netherlands (middle) and zoomed into the sandy soils of the Central Netherlands (Veluwe region – lower line of map subsets). For 2020–2021, we used the 120 forest soil samples over the Veluwe (with no repeat sampling at the same location between years) to interpolate soil pH (using inverse distance weighting, IDW) at a 30 m grid (Fig. 3 – lower line). Our field measured soil pH values reveal an alarming increase in hotspots of severely acidic soil (blue colour, Fig. 3) over the central Netherlands (Veluwe area) when compared with the LUCAS data set.

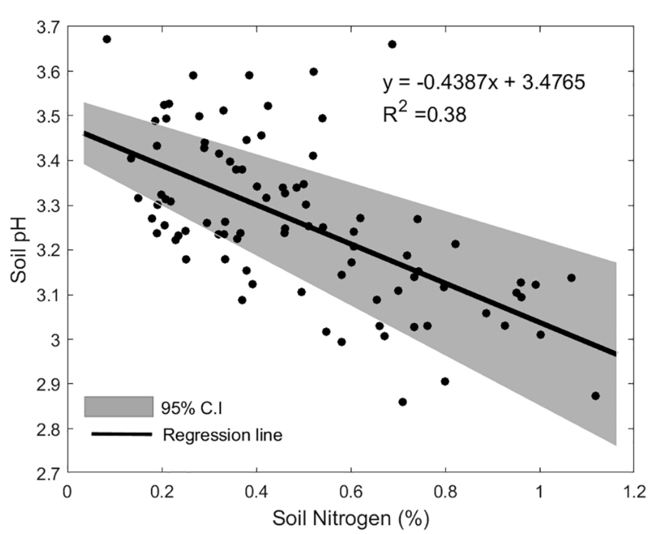

Fig. 2. Relationship between soil nitrogen content (%N) and soil pH on Natura 2000 forests in the Veluwe region including Veluwezoon, the Royal Estate Het Loo, and the Hoge Veluwe National Parks, the Netherlands.

Reports cited only the average field measured soil pH for the sandy soils of the Veluwe Natura 2000 area for 1999, 2008, 2011 (Kopittke et al., 2012) and 2019 (Rijneveld, 2020). These were plotted along with the LUCAS average pH values (for 2009, 2015 and 2018) as well as our own average soil pH data (for 2020 and 2021) (Fig. 3). Note that the average pH value used here is the true value (e.g., as calculated from the average molarity (Wolkersdorfer, 2023)). There has been a dramatic decline in average soil pH over the sandy soils of the Veluwe region over the last 22 years, from about pH 4.5 to 3.2. By 2021, the trend line of the average forest soil acidity is in the pH range (that is pH = 2 to 3) of household vinegar (Cosmulescu et al., 2022).

Across Europe, for arable and grazing soils, the average soil pH is 5.2 in the A horizon in Ferro-Scandia crystalline bedrock, while alkali soils (average pH = 6.3) which occur in southern Europe, lie on carbonate rich soils (Fabian et al., 2014). The Netherlands is in the transition zone dominated by sediments of the last glaciation, with an average pH = 5 on arable and grazing soils. Fabian and colleagues report anthropogenic influences including atmospheric nitrogen deposition in agricultural soils are hardly detectable due to increased buffering capacity in these agricultural soils, whereas our field sampling in the adjacent reserve areas with lowering buffering capacity have lower soil pH, with an average pH = 3.2.

4. Government policy driven by atmospheric nitrogen deposition models

Surprisingly, there are few publications based on raw soil pH data collected in situ informing government policy, as governments rely on modeled nitrogen deposition data, and the correlation of acidic soils with nitrogen deposition through pH estimates derived from vegetation surveys (Rijksoverheid, 2020). Further, we found few (none recently) soil pH field measurements in the EU LUCAS database for nature conservation areas of the Veluwe, as this database focused on agricultural soil samples. The last major report to the Dutch government was for the period 1990–2020, with main results based on nitrogen deposition generated by climate models (CBS, 2022). Dutch and EU policy recognize airborne nitrogen deposition as the key factor impacting the environmental and water quality of agricultural, heathland, grassland, and forest soils (EC, 2021; Rijksoverheid, 2022), though N deposition alone does not capture the rapid soil acidification in recent years (Fig. 4). This is because EU and Dutch government appear to have a time-lag ingesting real-world soil pH field data for national parks and nature conservation areas; up-to-date field pH measurements are required to recalibrate dynamic biogeochemical models which relate N atmospheric deposition and soil pH, thereby providing timely information to government and industry about atmospheric pollutants producing severely acidified soils. This time-lag challenge with a requirement for up-to-date field pH measurements is further amplified by the focus of the EU LUCAS database on agricultural and production forest areas, with under-sampling of field sample plots located on Natura 2000 areas. Government regulatory decisions and actions to reduce nitrogen deposition seem unaware of the existence of these large areas of severely acidic forest soils, and regulations probably require even higher reductions in nitrogen deposition to be effective.

5. Concluding remarks

Deposition of nitrogen compounds is a global environmental issue, with some regional areas in Europe under severe stress. The economic success of farmers and ever-growing agricultural output from

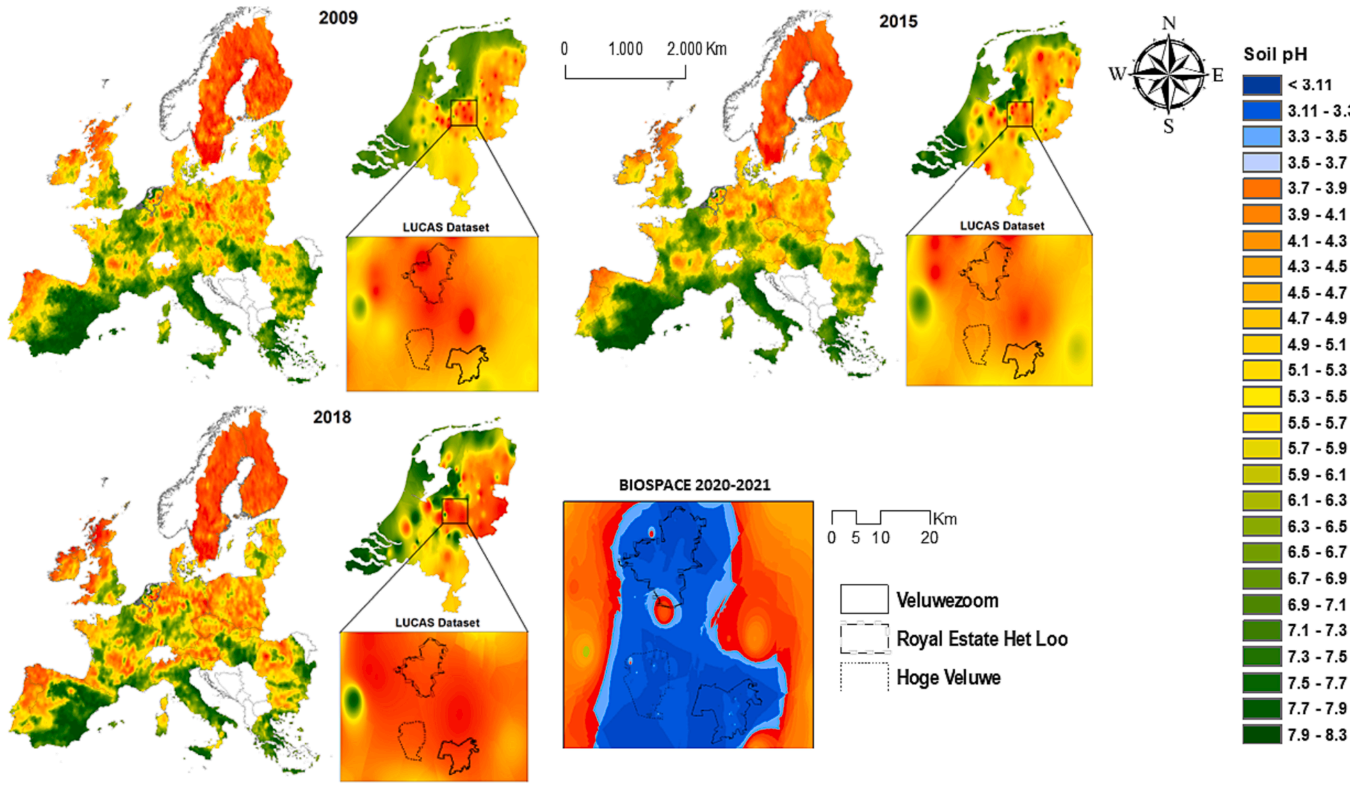

Fig. 3. Interpolated soil pH over Europe, the Netherlands, and the Veluwe region (shown as inset) from the LUCAS field plot soil database (2009, 2015, 2018). The soil pH for our field data collected over the Veluwe region (incorporating the Veluwezoom, the Royal Estate Het Loo, and the Hoge Veluwe National Parks) in 2020–2021 demonstrates the extreme soil acidification.

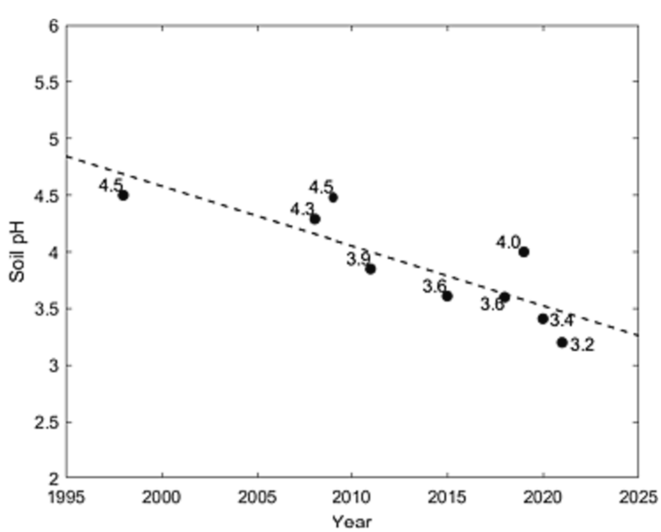

Fig. 4. Average soil pH per year for the Veluwe region, the Netherlands, spanning the years 1999–2018 (data from (Kopittke et al., 2012; Rijneveld, 2020), LUCAS database), supplemented by in situ field measurements collected during 2020–2021 for the purposes of this study.

increasingly intensive agriculture over a fixed area has an environmental cost which has emerged in Europe, and the Netherlands in an acute and widespread way. The Veluwe forests of the central Netherlands appear to be a microcosm of a larger problem throughout Europe – the environmental challenges posed by soil acidification. In the meantime, it appears the buffering capacity of the environment against acidification from deposition of nitrogen compounds, especially on vulnerable sandy soils in Natura 2000 forest areas, may be at its limits in parts of the Netherlands and EU. There are negative consequences from nitrogen deposition and soil acidification for biodiversity, farm productivity, soil sustainability, as well as surface and ground water pollution. Hotspots with a high N deposition are potential candidates for soil acidification, and we demonstrate here that the acidity of sandy forest soils in extensive Natura 2000 areas has been severely underestimated when modeled from atmospheric N deposition alone.

6. Recommendations

We recommend an urgent need for biennial field sampling of soil pH in Natura 2000 forest parks, specifically to (re-)calibrate soil pH when it is modeled from N deposition. There are multiple sources of nitrogen deposition in Natura 2000 forests which we recommend are included in N deposition models, including significant sources which are not yet included in models such as off lease dog walking areas. We recommend the delivery of properly calibrated remote sensing products through the EU Copernicus land services (Copernicus, 2020). Though nitrogen deposition and soil acidification are a wicked policy problem to solve, we recommend that the deposition of nitrogen compounds is significantly reduced for Natura 2000 forest areas.

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CRediT authorship contribution statement

A.K. Skidmore: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review

& editing. **H. Abdullah:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – review & editing. **A. Siegenthaler:** Conceptualization, Resources, Writing – review & editing. **D.P. Adiningrat:** Data curation, Resources, Writing – review & editing. **M. Rousseau:** Data curation, Resources, Writing – review & editing. **Y. Duan:** Data curation, Resources, Writing – review & editing. **A. Torres-Rodriguez:** Writing – review & editing, Resources, Conceptualization. **E. Neinavaz:** Data curation, Resources, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

Azevedo, L.B., van Zelm, R., Hendriks, A.J., Bobbink, R., Huijbregts, M.A.J., 2013. Global assessment of the effects of terrestrial acidification on plant species richness. Environ. Pollut. 174, 10–15. https://doi.org/10.1016/j.envpol.2012.11.001.

Basu, S., 2007. Chemical and biochemical processes for NOx control from combustion off-gases. Chem. Eng. Commun. 194 (10–12), 1374–1395. https://doi.org/10.1080/00986440701401537.

Bowman, W.D., Cleveland, C.C., Halada, L., Hresko, J., Baron, J.S., 2008. Negative impact of nitrogen deposition on soil buffering capacity. Nat. Geosci. 1 (11), 767–770. https://doi.org/10.1038/ngeo339.

CBS. (2022). *Stikstofdepositie 1990-2020*. Centraal Bureau voor de Statistiek (CBS). https://www.clo.nl/indicatoren/nl0189-stikstofdepositie.

CBS. (2023). *Grootschalige luchtverontreiniging de "National Emission Ceilings": emissies, 1990 - 2021*. Centraal Bureau voor de Statistiek (CBS). https://www.clo.nl/indicatoren/nl0183-verzuring-en-grootschalige-luchtverontreiniging-emissies.

Copernicus. (2020). *Copernicus Global Land Service: FAPAR*. VITO NV. Retrieved 2 November 2020 from https://land.copernicus.eu/global/about.

Cosmulescu, S., Stoenescu, A.M., Trandafir, I., Tutulescu, F., 2022. Comparison of chemical properties between traditional and commercial vinegar, 225 Horticulturae 8 (3). https://doi.org/10.3390/horticulturae8030225.

De Frenne, P., Cougnon, M., Janssens, G.P.J., Vangansbeke, P., 2022. Nutrient fertilization by dogs in peri-urban ecosystems. e12128 Ecological Solutions and Evidence 3 (1). https://doi.org/10.1002/2688-8319.12128.

Dirnbock, T., Proll, G., Austnes, K., Beloica, J., Beudert, B., Canullo, R., De Marco, A., Fornasier, M.F., Futter, M., Goergen, K., Grandin, U., Holmberg, M., Lindroos, A.J., Mirtl, M., Neirynck, J., Pecka, T., Nieminen, T.M., Nordbakken, J.F., Posch, M., Forsius, M., 2018. Currently legislated decreases in nitrogen deposition will yield only limited plant species recovery in European forests. Environ. Res. Lett. 13 (12), 125010 https://doi.org/10.1088/1748-9326/aaf26b.

EC. (2021). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Pathway to a healthy planet for all — EU action plan 'Towards zero pollution for air, water and soil'. E. Commission. https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12588-Towards-zero-pollution-in-air-water-and-soil-EU-action-plan_en.

EEA, 2014. Air pollution still harming Europe's ecosystems, despite reduced emissions. European Environment Agency. https://www.eea.europa.eu/highlights/air-pollution-still-harming-europe2019s.

EEA. (2020). *European Union emission inventory report 1990–2018 under the UNECE Convention on Long-Range Transboundary Air Pollution (LRTAP)*, (EEA Report 05/2020).

EEA. (2022). *Emissions of the main air pollutants in Europe*. European Environment Agency. Retrieved 25 November 2022 from https://www.eea.europa.eu/ims/emissions-of-the-main-air.

ESDAC. (2023). *LUCAS: Land Use and Coverage Area frame Survey*. European Commission, European Soil Data Centre (ESDAC), Joint Research Centre (JRC). Retrieved December 15 2023 from https://esdac.jrc.ec.europa.eu/projects/lucas.

Fabian, C., Reimann, C., Fabian, K., Birke, M., Baritz, R., Haslinger, E., G.P. Team, 2014. GEMAS: Spatial distribution of the pH of European agricultural and grazing land soil. Appl. Geochem. 48, 207–216. https://doi.org/10.1016/j.apgeochem.2014.07.017.

Forsius, M., Posch, M., Holmberg, M., Vuorenmaa, J., Kleemola, S., Augustaitis, A., Beudert, B., Bochenek, W., Clarke, N., de Wit, H.A., Dirnböck, T., Frey, J., Grandin, U., Hakola, H., Kobler, J., Krám, P., Lindroos, A.J., Löfgren, S., Pecka, T., Vána, M., 2021. Assessing critical load exceedances and ecosystem impacts of anthropogenic nitrogen and sulphur deposition at unmanaged forested catchments in Europe. Sci. Total Environ. 753, 141791 https://doi.org/10.1016/j.scitotenv.2020.141791.

Fowler, D., Brimblecombe, P., Burrows, J., Heal, M.R., Grennfelt, P., Stevenson, D.S., Jowett, A., Nemitz, E., Coyle, M., Lui, X.J., Chang, Y.H., Fuller, G.W., Sutton, M.A., Klimont, Z., Unsworth, M.H., Vieno, M., 2020. A chronology of global air quality, 20190314 Philosoph. Trans. Royal Soc. Math. Phys. Eng. Sci. 378 (2183). https://doi.org/10.1098/rsta.2019.0314.

Hartemink, A., de Bakker, H., 2002. Classification, Netherlands. In: Lal, R. (Ed.), Encyclopedia of Soil Science. Marcel Dekker. https://doi.org/10.1081/E-ESS-120022907.

Kopácek, J., Posch, M., 2011. Anthropogenic nitrogen emissions during the Holocene and their possible effects on remote ecosystems. Global Biogeochem. Cycles 25. Article Gb2017. https://doi.org/10.1029/2010gb003779.

Kopittke, G.R., Tietema, A., Verstraten, J.M., 2012. Soil acidification occurs under ambient conditions but is retarded by repeated drought: Results of a field-scale climate manipulation experiment. Sci. Total Environ. 439, 332–342. https://doi.org/10.1016/j.scitotenv.2012.09.044.

Liu, X.J., Xu, W., Du, E.Z., Tang, A.H., Zhang, Y., Wen, Z., Hao, T.X., Pan, Y.P., Zhang, L., Zhao, Y., Shen, J.L., Zhou, F., Gao, Z.L., Chang, Y.H., Goulding, K., Collett, J.L., Vitousek, P.M., Zhang, F.S., Zhang, Y.Y., Feng, Z.Z., 2020. Environmental impacts of nitrogen emissions in China and the role of policies in emission reduction, 20190324 Philosoph. Trans. Royal Soc. Math. Phys. Eng. Sci. 378 (2183). https://doi.org/10.1098/rsta.2019.0324.

Lu, Z., Streets, D.G., Zhang, Q., Wang, S., Carmichael, G.R., Cheng, Y.F., Wei, C., Chin, M., Diehl, T., Tan, Q., 2010. Sulfur dioxide emissions in China and sulfur trends in East Asia since 2000. Atmos. Chem. Phys. 10 (13), 6311–6331. https://doi.org/10.5194/acp-10-6311-2010.

Misselbrook, T., Bai, Z.H., Cai, Z.J., Cao, W.D., Carswell, A., Cowan, N., Cui, Z.L., Chadwick, D.R., Emmett, B., Goulding, K., Jiang, R., Jones, D.L., Ju, X.T., Liu, H.B., Lu, Y.L., Ma, L., Powlson, D., Rees, R.M., Skiba, U., Liu, X.J., 2022. Progress on improving agricultural nitrogen use efficiency: UK-China virtual joint centers on nitrogen agronomy. Front. Agric. Sci. Eng. 9 (3), 475–489. https://doi.org/10.15302/j-fase-2022459.

Qiao, X., Shu, X., Tang, Y., Duan, L., Seyler, B.C., Guo, H., Xiao, Y., Ying, Q., Zhang, H.L., 2021. Atmospheric deposition of sulfur and nitrogen in the West China rain zone: Fluxes, concentrations, ecological risks, and source apportionment. Atmos. Res. 256, 105569 https://doi.org/10.1016/j.atmosres.2021.105569.

Rijksoverheid. (2022). Aanpak stikstof. Rijksoverheid. Retrieved 1.12.2022 from https://www.government.nl/.

Rijksoverheid. (2020). *Geschiktheid zuurgraad bodem verzuringsgevoelige landnatuur, 2018*. https://www.clo.nl/indicatoren/nl1593-kwaliteit-verzuringsgevoelige-ecosystemen.

Rijneveld, A. (2020). *Analyse bosgrond: waar blijft het herstel?* EUROFINS. Retrieved 30.11.2022 from https://www.eurofins-agro.com/nl-nl/analyse-bosgrond-waar-blijft-het-herstel.

RIVM. (2023a). *AERIUS Monitor*. https://www.rivm.nl/aerius.

RIVM. (2023b). *MAN-gebied Veluwe Algemeen*. https://man.rivm.nl/gebied/veluwe_algemeen.

Wikipedia. (2023). *Nitrogen crisis in the Netherlands*. Wikimedia Foundation Inc. Retrieved 21 December 2023 from https://en.wikipedia.org/wiki/Nitrogen_crisis_in_the_Netherlands#:~:text=On%2029%20May%202019%2C%20the,future%20reductions%20in%20nitrogen%20deposition.

Wolkersdorfer, C. (2023). *Average pH-value*. https://www.wolkersdorfer.info/en/average-ph-value.html.

WUR. (2023). *Hogere prijzen zorgen voor recordwaarde landbouwexport en import in 2022*. Wageningen University and Research. Retrieved 21 December 2023 from https://www.wur.nl/nl/nieuws-wur/show/hogere-prijzen-zorgen-voor-recordwaarde-landbouwexport-en-import-in-2022.htm.

Xu, Y., 2013. Comparative Advantage Strategy for Rapid Pollution Mitigation in China. Environ. Sci. Tech. 47 (17), 9596–9603. https://doi.org/10.1021/es4010152.

Zhang, T.A., Chen, H.Y.H., Ruan, H.H., 2018. Global negative effects of nitrogen deposition on soil microbes. ISME J. 12 (7), 1817–1825. https://doi.org/10.1038/s41396-018-0096-y.

Zhang, Q.Y., Zhu, J.X., Wang, Q.F., Mulder, J., Liu, C.Q., He, N.P., 2023. Transformation from NH_x to NO_y deposition aggravated china's forest soil acidification. e2023GB007736 Global Biogeochem. Cycles 37 (6). https://doi.org/10.1029/2023gb007736.