

Laboratory of Atmospheric Processes and Impacts

Research Report:

Nitrogen or Us: Tracing the Silent Killer for Effective Air Policy

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1 Introduction

Nitrogen is fundamental to life on Earth, forming a key component of DNA, proteins, and chlorophyll, as well as constituting approximately 80% of our atmosphere. Although atmospheric dinitrogen (N_2) is naturally an inert, non-reactive gas, human activities over the last century have fundamentally transformed its global biogeochemical cycle. Fueled largely by synthetic fertilizer production through the Haber-Bosch process, intensive fossil fuel combustion, and munitions manufacturing, the total environmental flow of surplus reactive nitrogen (N_r) has doubled over the past 100 years. This massive anthropogenic surge in N_r has exerted unprecedented pressure on planetary boundaries, driving severe consequences across climate stability, energy security, food production systems, human health, and essential ecosystem services [1], [2], [3].

1.1 Types of Reactive Nitrogen and Atmospheric Transport

Reactive nitrogen exists primarily in two major chemical categories:

- **Oxidized species:** Including nitrogen oxides (NO_x , such as NO and NO_2).
- **Reduced species:** Specifically gaseous ammonia (NH_3) [4], [5].

Once emitted, these compounds circulate through the atmosphere and eventually enter terrestrial and aquatic ecosystems via two primary pathways: wet deposition (contained in rain and snow) and dry deposition (in the form of ambient gases and particulate matter). Additionally, excess nitrogen directly leaches from agricultural soil treatments into surrounding water bodies and deep groundwater reserves. Spatial and temporal deposition rates vary significantly across regions, dictated by local emissions, ambient atmospheric concentrations of nitrogen and other species, the presence of interacting ions, relative humidity, ambient temperature, and, hence the resulting aerosol acidity (pH).

1.2 Effects on the Environment

The persistent atmospheric deposition of reactive nitrogen species inflicts widespread environmental degradation. It degrades vegetation diversity, triggers freshwater and coastal eutrophication, causes severe soil acidification[6], contaminates drinking water, depletes stratospheric ozone, and drives emissions of nitrous oxide (N_2O) - a potent greenhouse gas. Furthermore, atmospheric N_r contributes to the formation of fine secondary particulate matter ($PM_{2.5}$), posing severe cardiovascular and respiratory health risks to human populations [7], [5].

Historically, air quality regulations across Europe successfully curbed sulfur oxides (SO_x) and fossil fuel-derived NO_x . However, reduced nitrogen emissions, specifically agricultural NH_3 , have remained largely unchanged [8].

1.3 Decarbonization Trade-offs and Sectoral Feedback

This challenge is further complicated by ongoing global decarbonization efforts. While phasing out fossil fuels gradually reduces conventional NO_x emissions, the transition toward renewable energy carries unexpected trade-offs:

1. Expanding biomass combustion and biofuel reliance threatens to increase both NO_x and NH_3 emissions.
2. Agricultural cultivation of bioenergy crops amplifies global demand for synthetic fertilizers.

Concurrently, demographic trends, such as rapid urbanization and rising per capita food consumption, continue to accelerate nitrogen loading in atmospheric and aquatic networks worldwide, a pattern clearly observable in Switzerland. Because the biogeochemical nitrogen cycle intrinsically links atmospheric, terrestrial, and aquatic compartments, isolated sector-specific research fails to capture cross-compartmental feedbacks. Mitigating nitrogen pollution requires a unified, cross-disciplinary scientific framework[9].

1.4 Governance Deficits

A critical obstacle in mitigating nitrogen pollution is the current lack of rigorous political governance, particularly regarding the agricultural sector. A prominent example is the European Commission’s recent adoption of revised rules allowing higher application thresholds for RENURE (**RE**cycled **N**itrogen recovered from man**URE**) fertilizers under the Nitrates Directive.

This decision raised significant concerns among environmental scientists and civil society advocates due to a distinct lack of transparency, democratic accountability, and scientific rigor. By expanding nitrogen limits above the established threshold of $170 \text{ kg N} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$ without conducting a full environmental impact assessment or public consultation, policymakers bypassed key safeguards established under EU climate and water protection laws.

Furthermore, recent scientific findings, indicating that recycled manure products can only substitute roughly 10% of mineral fertilizers and that reducing agricultural intensity is the single most effective way to curb nitrogen pollution, were sidelined. Weakening regulatory frameworks in this manner risks escalating nitrate accumulation in vulnerable soil and water systems while locking agriculture into an unsustainable, high-input paradigm [10].

1.5 Research Motivation

To bridge the gaps between atmospheric science, policy deficits, and ecological protection, I utilized high-resolution thermodynamic modeling to continuously map the acidity of suspended, fine atmospheric particles (aerosol pH). Based on ambient temperature and relative humidity, this framework determines whether reactive nitrogen species exist predominantly in the gas phase or as suspended particulate matter through gas-particle partitioning regimes (referred to as sensitivity regimes from now on).

By identifying where reactive nitrogen remains suspended in the atmosphere, forming harmful fine particles, and where it deposits into sensitive ecosystems, this study provides the precise spatial diagnostics necessary to design targeted, chemically sound air quality and environmental protection policies across Europe.

2 Research Design

The principal objective of this research was to model European atmospheric aerosol acidity (pH), validate the model output against observational datasets, and evaluate regional deposition and sensitivity regimes

using the thermodynamic framework developed by Prof. Athanasios Nenes [11].

The workflow began with processing, filtering, and transforming output data from the PMCAMx model for the year 2019. PMCAMx is a three-dimensional chemical transport model that provides meteorological and atmospheric composition data, including organic mass, trace gas concentrations, and major inorganic cation/anion species [12]. We chose to model at a spatial resolution of 36×36 km across Europe. The raw PMCAMx output was reformatted to meet the input requirements of the ISORROPIA-Lite II thermodynamic equilibrium model.

Once the data was properly formatted, I used ISORROPIA-Lite II to calculate aerosol pH across the European grid. Initial runs produced impossible pH values, so I ran a series of sensitivity analyzes on each input parameter to figure out what was driving the errors. As part of this troubleshooting process, I double-checked all unit conversions, evaluated the impact of mineral dust events, and filtered out data points where ambient temperature (T) or relative humidity (RH) fell outside the valid operational range for ISORROPIA. By closely examining the outlier grid cells, we realized there was an issue with the original PMCAMx input data, which was then corrected.

With the corrected dataset producing reasonable pH values, I validated the model using observational data from Swiss monitoring stations, specifically Beromünster, Payerne and Magadino. Before running the validation, I had to format the observational data from these stations to fit the required input structure. I then matched each site to its nearest PMCAMx grid cell and calculated the corresponding aerosol pH. To evaluate the results, I generated comparative graphs contrasting the modeled and observed values. The modeled and measured values aligned closely, confirming that the thermodynamic calculations were credible.

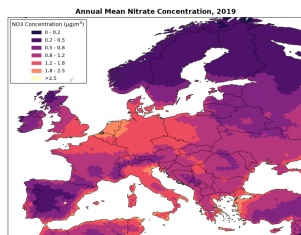
Next, I evaluated the gas-particle partitioning sensitivity and deposition regimes for both the observed and modeled datasets. Because they matched almost perfectly on an annual scale, I could conclude that the model output is reliable not just for Switzerland, but across the full European grid.

Finally, I interpreted these spatial and chemical patterns to derive comprehensive policy implications, targeting key drivers of reactive nitrogen pollution and aerosol formation across the region.

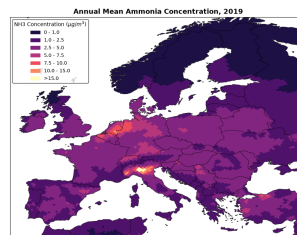
3 Results and Analysis

3.1 Spatial Distribution of Precursor Species

The atmospheric reactive nitrogen species’ distributions display distinct spatial patterns across Europe for the modeled year 2019. Nitrogen oxides (NO_x) exhibit a widespread, relatively uniform distribution across Western and Central Europe, primarily driven by fossil fuel combustion such as vehicle emissions. In contrast, ammonia (NH_3) concentrations are strongly localized, revealing major agricultural hotspots, most notably within the Po Valley in Northern Italy and the Netherlands, where intensive livestock farming and fertilizer applications dominate atmospheric inputs.



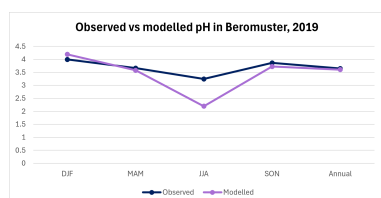
(a) Annual Mean Nitrate (NO_3^-) Concentration, 2019.



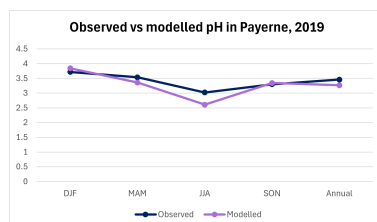
(b) Annual Mean Ammonia (NH_3) Concentration, 2019.

3.2 Model Validation against Swiss Observational Sites

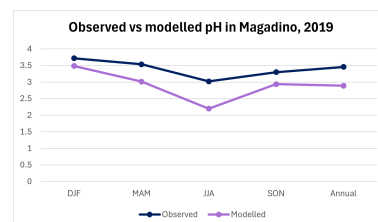
To verify the thermodynamic calculations, the modeled aerosol pH was compared directly against observations across key Swiss monitoring stations, including Beromünster, Payerne, and Magadino. Seasonal (DJF, MAM, JJA, SON) and annual comparisons demonstrate strong alignment between observed and modeled aerosol pH values.



(a) Beromünster



(b) Payerne

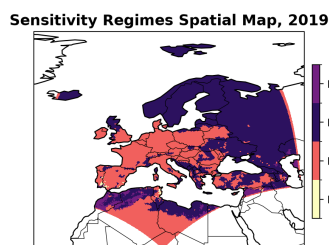


(c) Magadino

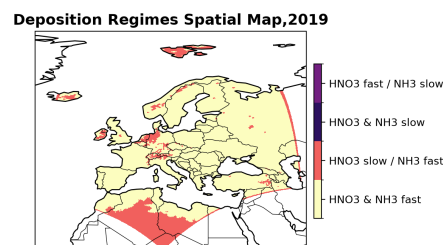
Notably, the robust agreement on an annual scale confirms that the thermodynamic model accurately reproduces aerosol acidity, providing a solid foundation for extending sensitivity and deposition regime analyses across the broader European region.

3.3 Sensitivity Regimes

Using the framework developed by Prof. Athanasios Nenes, spatial mapping of chemical sensitivity regimes reveals important insights for air quality and ecosystem management across Europe (Figure 3).



(a) Spatial Map of Sensitivity Regimes (2019).



(b) Spatial Map of Deposition Regimes (2019).

Figure 3: European spatial distribution of chemical sensitivity regimes and reactive nitrogen deposition dynamics.

- **Sensitivity Regimes:** As depicted in Figure 3a, regions with high NH_3 concentrations, such as the agricultural hotspots in the Po Valley and the Netherlands, fall strictly under the HNO_3 -sensitive regime, which means that any and all nitric acid emitted will instantly be converted in particulate matter. In these areas, reductions in ammonia alone yield minimal reductions in air pollution, instead, targeted NO_x controls are strictly essential for effective $\text{PM}_{2.5}$ mitigation.
- **Deposition Regimes:** (Figure 3b) indicates that the vast majority of Europe falls under the " HNO_3 and NH_3 fast" regime. This rapid deposition behavior across the continent is governed by an interplay of atmospheric factors, including relative humidity, local aerosol acidity (pH), ambient temperature, and surface boundary layer dynamics, which collectively drive fast surface uptake for both species. Because both pollutants settle rapidly out of the atmosphere across most of Europe, effective environmental policies must strictly limit emissions of both NO_x and NH_3 simultaneously. Alongside this broad pattern, specific key zones categorized as " HNO_3 slow / NH_3 fast" correspond directly to agricultural hotspots, where rapid local ammonia volatilization and deposition drive intense, localized reactive nitrogen loading onto nearby ecosystems. On the contrary, all nitric acid emissions in these zones get partitioned into particles and stay in the atmosphere for a prolonged amount of time.

4 Conclusions

This research highlights the critical role of atmospheric aerosol acidity (pH) and thermodynamic equilibrium modeling in evaluating reactive nitrogen deposition and fine particulate matter ($\text{PM}_{2.5}$) formation across Europe. Based on these findings, several key science-backed policy implications emerge:

- **Target Limiting Reagents:** Air quality management must tailor emission reduction strategies to regional sensitivity regimes rather than relying on uniform, broad-spectrum regulations.
- **Targeted Regional Controls:** Policies should prioritize limiting NO_x emissions across dense urban and transport corridors, while focusing specifically on NH_3 reductions within localized agricultural hotspots such as the Po Valley and the Netherlands.
- **Cross-Sectoral Policy Integration:** Effective pollution mitigation requires bridging environmental policy across transportation, industry, and agricultural sectors to align regional emissions targets.
- **Agricultural Subsidies and Sustainable Practices:** Mandating and financially subsidizing the adoption of sustainable farming techniques, such as low-emission manure storage, precise fertilizer application, and livestock feed optimization, is essential for curbing ammonia emissions at the source.

To further expand upon this foundation, future research should extend this thermodynamic framework beyond the single-year benchmark of 2019 to construct longitudinal multi-year maps. Furthermore, incorporating future climate change projections and green transition scenarios will provide a more dynamic, robust evidence base for designing resilient, long-term environmental policies.

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