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EDITORIAL

Focus on reactive nitrogen and the UN sustainable development goals

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Abstract

The scientific evidence assembled in this Focus Collection on ‘Reactive nitrogen and the UN sustainable development goals’ emphasizes the relevance of agriculture as a key sector for nitrogen application as well as its release to the environment and the observed impacts. Published work proves the multiple connections and their causality, and presents pathways to mitigate negative effects while maintaining the benefits, foremost the production of food to sustain humanity. Providing intersections from field to laboratory studies and to modelling approaches, across multiple scales and for all continents, the Collection displays an overview of the state of nitrogen science in the early 21st century. Extending science to allow for policy-relevant messages renders the evidence provided a valuable basis for a global assessment of reactive nitrogen.

Environmental sciences should have a major bearing on relevant policies, but scientific societies and publication pathways are seldom designed to deal with science and policy together. In association with the International Nitrogen Initiative (INI), we are glad to present this unique collection of articles relevant to both. The work presented highlights various aspects of assessment and management of reactive nitrogen (Nr), as well as their relevance to the various sustainable development goals, guided by the focus of the 8th INI Conference, held online between 30 May and 3 June 2021. Some of these articles are from conference participants while others have been contributed by the wider community in response to an open call from this journal.

INI’s main goal has been to optimize the benefits of Nr in sustainable food production and minimize its negative effects. Nr compounds such as nitrous oxide, ammonia and nitrogen oxides in air and in water, nitrates, nitrites as well as organic nitrogen affect human health, the environment, biodiversity and climate from food production, fuels, industry, waste and other sources. The INI conferences have accompanied the journey of the Nr community to address their science and policy aspects for over two decades. The efforts for intergovernmental recognition of Nr as a global concern were rewarded with the adoption of the first ever UN resolution on sustainable nitrogen management (Sutton *et al* 2019, UNEP 2019, Raghuram *et al* 2021). Consequently, the 8th INI Conference was hosted by a national government for the first time: the German Environment Agency with the support of the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection. The Berlin Declaration[9] resulting from this conference, issued jointly by the German government and the INI, heralded a new era of science–policy cooperation, specifically calling for integrated management of nitrogen (N) compounds instead of specifically addressing individual problem areas.

9 https://ini2021.com/berlin-declaration/.

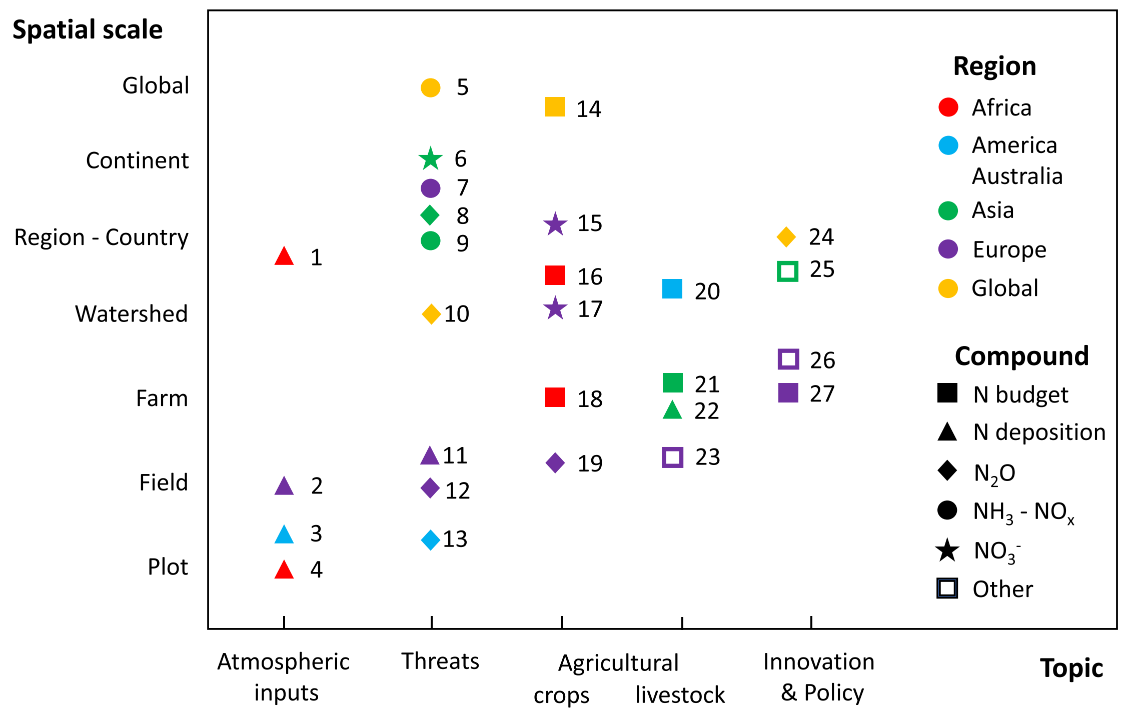

Figure 1. Topics and scales covered by papers in this Focus Collection. Papers are represented as follows: 1, Bakayoko *et al*, ERL; 2, van der Graaf *et al*, ERC; 3, Costa *et al*, ERL; 4, Ossohou *et al*, ERL; 5, van Damme *et al*, ERL; 6, Nishina *et al*, ERC; 7, Skiba *et al*, ERL; 8, Bansal *et al*, ERL; 9, Wen *et al*, ERL; 10, Webb *et al*, ERL; 11, Hood-Novotny *et al*, ERC; 12, Medinets *et al*, ERL; 13, Friedl *et al*, ERL; 14, Kaltenegger *et al*, ERC; 15, Spijker *et al*, ERC; 16, Ntinyari *et al*, ERC; 17, Hansen *et al*, ERL; 18, Gweyi-Onyango *et al*, ERL; 19, Byers *et al*, ERC; 20, Li *et al*, ERC; 21, Toda *et al*, ERC; 22, Yi *et al*, ERL; 23, Löw *et al*, ERC; 24, Amon *et al*, ERL; 25, Yang *et al*, ERL; 26, Stuhr *et al*, ERC; 27, Löw *et al*, ERL. ERC, *Environmental Research Communications*; ERL, *Environmental Research Letters*.

It is this organizational framework to which the individual contributions to the Focus Collection have been contributing. The science of N is diverse and multidisciplinary, comprising varied topics studied at different spatial scales and involving several N compounds. The scientific papers presented here deal with many of the main N topics, scales and compounds in a diverse geographical context (figure 1). With a focus on Europe (ten papers), Africa (four papers), Asia (six papers), America and Australia (three papers) are also represented, as well as global approaches (four papers). Both spatial and system scales affect methods, boundaries, conclusions and recommendations. Contributions considering plot, field and farm scales are fundamental for building basic knowledge (13 papers), but those working at larger scales from watershed to global (14 papers) are essential to integrate the basic knowledge for providing sound and generalizable conclusions and recommendations. Similarly, N studies can be found here that focus on one of the various reactive N compounds (mainly NH_3, N_2O and NO_3^-) or that consider integrated approaches such as N budgeting. While it is impossible to cover all the possible combinations of approaches, this Focus Collection includes many and as such represents the multidimensional nature of N science.

Nr compounds serve as nutrients for plant growth in terrestrial and aquatic ecosystems. Atmospheric input is a key factor characterizing the functioning of such systems. Experimental results presented in this Focus Collection show increasing trends of wet N deposition since the year 2000 (Ossohou *et al* 2021) for a western African savanna site; however, this is compensated for by decreasing dry deposition. Biomass burning and agriculture are singled out as the most important sources of atmospheric N deposition. For the Lake Victoria region in Kenya, Bakayoko *et al* (2021) present a long-term monitoring time series of wet N deposition and they conclude that due the elevated loads of atmospheric N, the Lake Victoria system is exposed to eutrophication in the long term. In contrast, European N deposition is projected to decline in the next decades due to international and national air quality regulations. Along with that, risks for terrestrial biodiversity through eutrophication are tentatively expected to decline in Europe (Jonson *et al* 2022). Still, atmospheric deposition in Europe is not only affecting biodiversity but also strongly influencing carbon sequestration in terrestrial ecosystems. Clear responses of forest gross primary production in Europe in comparison with annual N deposition are shown by van der Graaf *et al* (2021). While these authors could not identify N deposition affecting the response of European forest productivity to droughts, N addition experiments in Brazilian savannas (Costa *et al* 2021) suggest that eutrophication may cause changes at an anatomical level in the xylem vessels of woody species, thus making them more vulnerable to cavitation and potentially also to droughts.

N pollution poses threats in several environmental domains, often summarized as WAGES: water, air, greenhouse gases, ecosystems and soils (Sutton *et al* 2011). We note new findings in all these domains. On water pollution, Nishina *et al* (2021) find that the total inorganic nitrogen (TIN) loading arriving through the rivers at the East China Sea has largely increased since 1970. Despite improvements in nitrogen use efficiency (NUE) and a reduced increase in TIN loading since the 2000s, the residual load is still too high for the sensitive ecosystem of the shallow continental shelf of the East China Sea. Regarding air pollution, van Damme *et al* (2021) observe a massive increase in global ammonia emissions based on hyperspectral infrared satellite sounders. Between 2008 and 2018, ammonia emissions rose by 12.8%, with hotspots in the North China Plain, Pakistan and the Ganges watershed, and West and Central Africa. Ammonia, together with gaseous nitric acid, are shown to also play a dominant role in secondary inorganic particle formation ($PM_{2.5}$) in Beijing (Wen *et al* 2021). While NH_3 results from persistent non-agricultural activities (e.g. traffic) and periodic agricultural emissions, NO_x emissions are mostly the result of combustion processes. Other NO_x sources become relevant only after successful abatement. Skiba *et al* (2021), for Europe, demonstrate the increased importance of agricultural and forest soils as a source of NO, even though limited available data indicate that their contribution might be overestimated. Among greenhouse gases, N_2O is an intrinsic element of the N cycle. The conditions promoting N_2O formation in agricultural soils still need to be better understood for accurate representation in models and to give advice for abating emissions. Friedl *et al* (2021) use field measurements for Australian sites to identify an exponential effect of soil water content on N_2O emissions, as well as the important role of heterotrophic nitrification. Also, Medinets *et al* (2021) point to the importance of dry–wet pulses and highlight that natural NO and N_2O emissions should also be considered in national inventories given their high background emissions, especially as they may increase due to global warming (Gao *et al* 2022). Indirect emissions of agricultural fertilization through leaching are still poorly represented in emission inventories. Webb *et al* (2021) argue that leaching to artificial agricultural waters, for example drains, ditches or irrigation canals, should be accounted for separately because emission factors are considerably lower than for rivers or lakes. Yet, as Maavara *et al* (2019) point out, current Intergovernmental Panel on Climate Change (IPCC) emission factors for rivers and lakes may also be too high. Bansal *et al* (2022) remind us of N_2O sources beyond agriculture. These authors find a doubling of N_2O emissions from fuel combustion in South Asia between 1990 and 2017, and these are expected to increase even more strongly by 2040. Changes in N inputs can also change ecosystems fundamentally. Hood-Nowotny *et al* (2021) find that the high inorganic nitrogen load caused by atmospheric deposition on Austrian forests inhibits fungal activity. These forests are not adapted to high N loads; microbial activity does not further increase due to N saturation. Soils are therefore altered strongly by N deposition. Hood-Nowotny *et al* (2021) observe that soil organic matter stocks increase because of N deposition, as decomposition by microbes is limited by factors other than N while fungal decomposition is impeded by too much N. This finding is in line with the meta-analysis by Janssens *et al* (2010), but has so far not been quantified at a global scale (Schulte-Uebbing and de Vries 2018).

As agriculture benefits from N nutrients, both the environmental impacts associated with N release and the options for reducing such impacts are key research topics. The challenge of optimizing N inputs in plant production is global. Hence, Kaltenegger *et al* (2021) use global gridded data to develop maps of N surplus on grazing and agricultural land—pointing to insufficient knowledge about land use (as from land use maps) as the single parameter most critical for improvement, but also providing an overview of surplus (and release potential) on a $0.5° \times 0.5°$ grid scale. Information on N surplus and use is central for better N handling, and experimental evidence guides the way forward. For Africa, a region notoriously lacking agricultural nutrients, application efficiency is the core of all considerations. Management conditions of irrigated rice, identifying the right varieties and cropping season while maintaining modest N addition, proved essential for avoiding environmental damage at high production levels at two sites in Kenya (Gweyi-Onyango *et al* 2021). The trends and scenarios of NUE in smallholder farms were determined for the Lake Victoria region, also in East Africa (Ntinyari *et al* 2022). Results indicate the need to improve yields and avoid soil mining rather than increasing NUE. Management decisions and measures dedicated to reducing environmental release of N compounds to the environment are the common element for studies performed for conditions in Europe. Nitrous oxide emissions driven by freeze–thaw cycles in Norway (Byers *et al* 2021) depend on the type of plant substrate rather than on the amount of N available, with pure clover cultivation providing much higher off-season emissions than mixed grass–clover or grass-only control plots, even if fertilized. More winter-hardy 'catch crops' may help prevent N mineralization and subsequent microbial conversion. Denitrification and the subsurface redox structures have been the subject of study by Hansen *et al* (2021). These authors assess potential nitrate leaching to groundwater in Denmark using data for three watersheds and extrapolating for the whole country based on geological and geochemical conditions to define risk zones and thresholds. In particular, marine deposit soils and moraine landscapes demonstrate complex redox conditions. Statistical methods for quantifying nitrate leaching in the Netherlands have been developed by Spijker *et al* (2021), who use machine learning algorithms ('random forest') to connect observed and predicted quantities at 500 m resolution for the whole country.

NUE is also a decisive indicator in animal husbandry. Toda *et al* (2020) estimated N balances and compared the NUE of dairy farms in Japan using either a total mixed ration (TMR) and biogas system or conventional feeding. They found a considerable variability in N surplus and NUE and identified the stocking rate and feed N as the main influencing factors. TMR farms had a higher productivity and less variation in NUE. The authors recommend improving pasture management and the share of homegrown feed to reduce N surplus. Löw *et al* (2020) increase our knowledge on the effect of different grazing intensities on NUE, focusing on northwest Germany. All systems from full grazing to zero grazing management systems revealed a N surplus, but the surplus decreased when the share of grazing decreased. However, farm NUE varied greatly between farms, and there is large scope for improvements without changing grazing management, or even switching to zero grazing. Li *et al* (2021) investigated the potential of sustainable intensification of grass and corn production for dairy farms in Canada to improve nutrient management. Increasing the share of corn production and decreasing the share of grass will increase farm productivity; however, good care must be taken to avoid pollution swapping. These authors stress the importance of good agricultural practices for achieving sustainable intensification. Finally, Yi *et al* (2021) quantified the impacts of an intensive fattening pig farm in central China, where about one tenth of the NH_3 emissions was deposited within 500 m of the source.

While the global awareness of N as a topic has increased, the complexity of interacting Nr species is not well understood by decision-makers. Due to the reactions and interactions of reactive species and their exchange between environmental compartments, coherent policies require integrative approaches. Yang *et al* (2022) analyse the N-related legislation of South Asian countries. Interestingly, less than 10% of nearly a thousand political measures consider multiple pollution sources, sectors, nitrogen threats and impacts with integrative policy instruments. These authors also find legislation that leads to more consumption of Nr and they provide a classification of different policy options with respect to their relevance to combat Nr release. In northern and western Europe, tools have been introduced to reduce Nr emissions from sources such as traffic, agriculture and wastewater. Two studies from Germany focus on the current regulations and their impact. Löw *et al* (2021) examine the suitability of three different approaches for limiting excess N fertilizers, i.e. net soil surface balance, gross farm-gate balance and fertilization planning. Their analysis of 6000 farms can help to design better-targeted regulations. Stuhr *et al* (2021) studied the constraints for pig farmers under German law to adopt N-reduced farming practices. Some farmers feel weary of the current requirements, others change their routine management only partially and a third group adapts to the necessary changes proactively. However, the overall result is not satisfying. The authors identified type-specific constraining factors that should be considered in future regulation. Policy also needs reliable data: Amon *et al* (2021) investigate the effects of using different IPCC reporting guidelines on the emission estimates from the livestock sector, with Austria as a case study. They find important shifts in the relation between the main emission sources, when moving from the 1996 guidelines to the updated version of the 2006 guidelines or taking advantage of the 2019 refinement. Increased CH_4 emissions from enteric fermentation and manure management and a decrease of indirect N_2O emissions and of N_2O from manure management and soils are the consequence of methodological change, pointing out the need to harmonize methods for benchmarking and comparison.

Previous efforts similar to those covered here led to regional assessments of the environmental impacts of Nr—the European Nitrogen Assessment (Sutton *et al* 2011), the National Nitrogen Assessments of India (Abrol *et al* 2017) and Pakistan (Aziz *et al* 2021), making South Asia an important global hub of action. For California, Tomich *et al* (2016) demonstrate an assessment at sub-country scale. Now INI currently oversees, in the framework of the ongoing International Nitrogen Management System (INMS) project, a global extension of such activities, the first ever International Nitrogen Assessment scheduled for 2023. That activity will also draw on the results published in this Focus Collection.

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