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Evaluation of global research on agricultural nitrogen pollution between 1990 and 2023: Challenges for more efficacy and equity

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A B S T R A C T

Excessive and inefficient nitrogen (N) use in agriculture poses pervasive environmental threats for Water quality, Air quality, Greenhouse gas emissions, Ecosystems and biodiversity, and Soil (WAGES). However, it is unclear whether the global distribution of research corresponds to the severity of these threats. Here we provide a global assessment linking research outputs across WAGES with cropland N surplus, a proxy for the severity of N threats. We show that N surplus correlates well with the number of publications addressing WAGES threats, although marked regional disparities exist. Higher income countries distribute research more evenly across threats associated with high fertiliser inputs, while lower income countries prioritise soil research, particularly soil fertility. Publications from lower income countries account for only 8 % of the total and focus largely on food security rather than on N pollution. Since these countries are responsible for half of global N losses, they represent important "low hanging fruits" where targeted research can simultaneously improve food security and reduce N pollution. Our study highlights the need to strengthen research capacity, support locally led priorities, and better align research investments with the severity of N threats to advance toward more equitable and effective N management.

1. Introduction

Nitrogen (N) pollution from agriculture poses an urgent and multifaceted threat to the environment, human health and climate. The excessive and inefficient use of agricultural N inputs triggers a cascade of environmental impacts, simultaneously affecting water, air, soil and ecosystems (de Vries et al., 2024). Reactive N compounds such as nitrate (NO_3^-), ammonia (NH_3) and nitrous oxide (N_2O) contaminate drinking water (Bijay-Singh and Craswell, 2021), degrade air quality (Liu et al., 2023), accelerate climate change (Gong et al., 2024) and disrupt biodiversity (van der Plas et al., 2024). These interconnected N threats also pose serious public health risks, ranging from respiratory diseases (Guo et al., 2024) to cancer (Mendy and Thorne, 2024). Conversely, low or absent N inputs can be equally detrimental, leading to soil degradation and severe yield losses as soil N and carbon stocks are progressively exhausted (Harerimana et al., 2023).

Framing these diverse and overlapping impacts is essential for informing effective scientific and policy responses. To capture the full scope of N environmental impacts, the WAGES framework, which covers Water, Air, Greenhouse balance, Ecosystems and Biodiversity, and Soil, was introduced in the European Nitrogen Assessment (Sutton et al., 2011). This framework was designed to make the complexity of N

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pollution more manageable and actionable by classifying the major N threats. The environmental compartments covered by WAGES are not isolated as reactive N compounds can quickly shift from one to another (e.g., NH_3 emissions can be deposited into soils or waterbodies), creating feedback loops and trade-offs that render individual solutions ineffective (You et al., 2023). The WAGES framework thus provide a holistic lens to evaluate N threats and guide integrated cross-sectoral policy responses (Kanter et al., 2020).

While the WAGES framework clearly defines the environmental N threats, addressing them in practice remains challenging. Effective policies and management strategies must overcome major implementation barriers. Implementing best management practices could generate economic benefits of more than 400 billion USD annually (Gu et al., 2023). However, adoption is limited by socioeconomic barriers (Ren et al., 2022) and policy challenges (Kanter et al., 2020), including limited financial incentives and a lack of access to knowledge and advisory systems (Ibrahim and Hou, 2023). Policy initiatives play a critical role in guiding stakeholders towards improved N management, but the scientific community plays an equally important role in driving innovation and informing priorities.

The scientific community has demonstrated substantial regional differences in N pollution (de Vries et al., 2024; Lassaletta et al., 2016), agri-environmental policies (Wuepper et al., 2024) and the potential for improving management practices (You et al., 2023). Even the distribution of research intensity itself is uneven, shaped by structural inequalities in funding and institutional capacity (Padilla et al., 2018). Despite major advances in the last few decades, the real-world impact of N research in addressing societal and environmental changes remains poorly understood (Zhang and Yu, 2020). This critical gap deserves urgent attention as the effective allocation of scientific and financial resource is important to achieve both societal and environmental goals within safe planetary and regional boundaries (Rockström et al., 2023; Schulte-Uebbing et al., 2022).

Here, we assess whether global research efforts on agricultural N threats align with societal and environmental needs using the WAGES framework. We examine how these research patterns are contributing to improvements in N use efficiency (NUE) in agriculture and identify regional priorities and potential low hanging fruits for targeted research investment. We also map the institutional and funding structure that shape the global N research landscape. To achieve this, we: (i) conduct a multi-scaled, data-driven assessment of agricultural N threat research across income levels and N management contexts for the period 1990–2023 and (ii) evaluate the relationship between research efforts and cropland N surplus, here used as a proxy for the severity of N threats. Our integrated approach provides an important foundation for identifying where additional research could have the greatest impact, guiding future work toward regions and N threats where scientific and societal needs are most misaligned.

2. Methods

2.1. Systematic review

We compiled a bibliometric dataset focussed on N management in agriculture and its impacts for the period 1990–2023 by querying the Web of Science database. The full search string combined N related terms with agricultural filters, returning 38923 publications:

All fields - (("nitrogen management") OR “nitrogen” OR (N2O OR NOx OR NH3 OR NO3 OR (Nitrous AND oxide) OR Ammonia OR Nitrate* OR (Nitric AND Oxide)); Topic - (agriculture OR farm* OR livestock OR crop) AND (Topic - (Nitrogen AND (Fixation OR Fertilization OR Fertilisation OR Deposition OR Leaching OR Volatilization OR Runoff OR Pollution OR Contamination OR Mitigation OR Emission*).

Our objective was to assess how research on agricultural N management aligns with the five key environmental threats defined by the WAGES framework.

2.2. Grouping research keywords per N threat

We grouped research keywords from the bibliometric dataset according to the five WAGES N threats (i-v). Publications without keywords (n = 5775) were filtered out before assigning and categorising research keywords (see Fig. S1 for PRISMA flowchart). This procedure allowed for the inclusion of keywords based on important underlying processes and impacts within each environmental compartment (Table S1).

First, the threat of Water quality focussed on the runoff and leaching of NH_4^+, NO_3^-, and other dissolved organic N forms into ground- and surface waters in the context of eutrophication.

Second, the threat of for Air quality addressed NO_x, NO_2 emissions, NH_3 volatilisation and their impact on the formation of secondary particulate matter and tropospheric ozone.

Third, the GHG balance threat examined the emissions of N_2O, CH_4 and CO_2.

Fourth, N impacts on Ecosystems and Environment included the effects of N deposition and increased N availability on terrestrial and aquatic biodiversity through acidification and eutrophication in N sensitive areas (e.g., Natura 2000 network).

Lastly, the N threat to Soil quality included soil biodiversity related to N cycling, the impacts of excessive N availability such as soil acidification and reduced soil organic matter quality, and the risk of soil fertility loss under insufficient N inputs.

After we applied keyword filtering via automated text mining, the final dataset contained 20369 publications.

2.3. Classifying countries according to socioeconomic conditions and N management

We quantified the number of publications per N threat at regional and national levels by ascertaining the country affiliation for of authors. Publications were further aggregated according to socioeconomic conditions and N management, using both income level and NUE (%; Fig. S2). Income data were derived from World Bank (2024), and national-level NUE data from Ludemann et al. (2024), available for the period 1990–2021, which defined the scope of our analysis.

Countries were clustered into four groups based on Gross National Income (GNI; \$ $capita^{-1}$ yr^{-1}) as defined by the World Bank (2024): low- (<1145), lower- (1146–4515), upper- (4516–14005) and high- (>14006) income. Each income category was further subdivided by NUE level following EU Nitrogen Expert Panel (2015) guidelines: very low (<50 %), desired (50–90 %) and very high (>90 %). NUE was calculated as the ratio of N output in harvested products to the sum of N inputs, which included biological N fixation, synthetic and organic fertilisers, atmospheric deposition and seeds. Very low NUE indicates high N losses, while values above 90 % suggest soil N mining.

Using the same input data, we estimated the N surplus as the difference between N inputs and N outputs. This allowed us to identify regions with varying degrees of N management efficiency and the corresponding research focus on N threats.

2.4. Comparing research with nitrogen threats from agriculture

We quantified the response of N threat research by analysing the number of publications per threat relative to the cropland N surplus, averaged over the period 1990–2021 (Ludemann et al., 2024). We used the N surplus as a proxy for the severity of N threats, as it is a widely used indicator of potential environmental N losses (Batool et al., 2025; Klages et al., 2020; Zhang et al., 2021) and is central to defining the safe operating space for N management (te Wierik et al., 2025).

The cropland N surplus was selected instead of actual N losses to air and water due to the high temporal and spatial variability of such losses, which limits their validation at regional and continental scales (Zhang et al., 2021). Livestock emissions from grazing and manure management were also excluded due to limited harmonisation across data sources, which would have compromised cross-country comparability. We acknowledge that this underrepresents certain N threats in livestock dominated countries with respect to Air quality, GHG balance and Biodiversity (Uwizeye et al., 2020). Nonetheless, an ad-hoc correlation analysis confirmed that the cropland N surplus is strongly associated with N leaching and NH_3 volatilisation from FAOSTAT (R^2>0.90), supporting its use as a proxy for overall N threats.

To assess whether the body of N research aligns with existing N threats, we fitted a linear regression for all regions per N threat

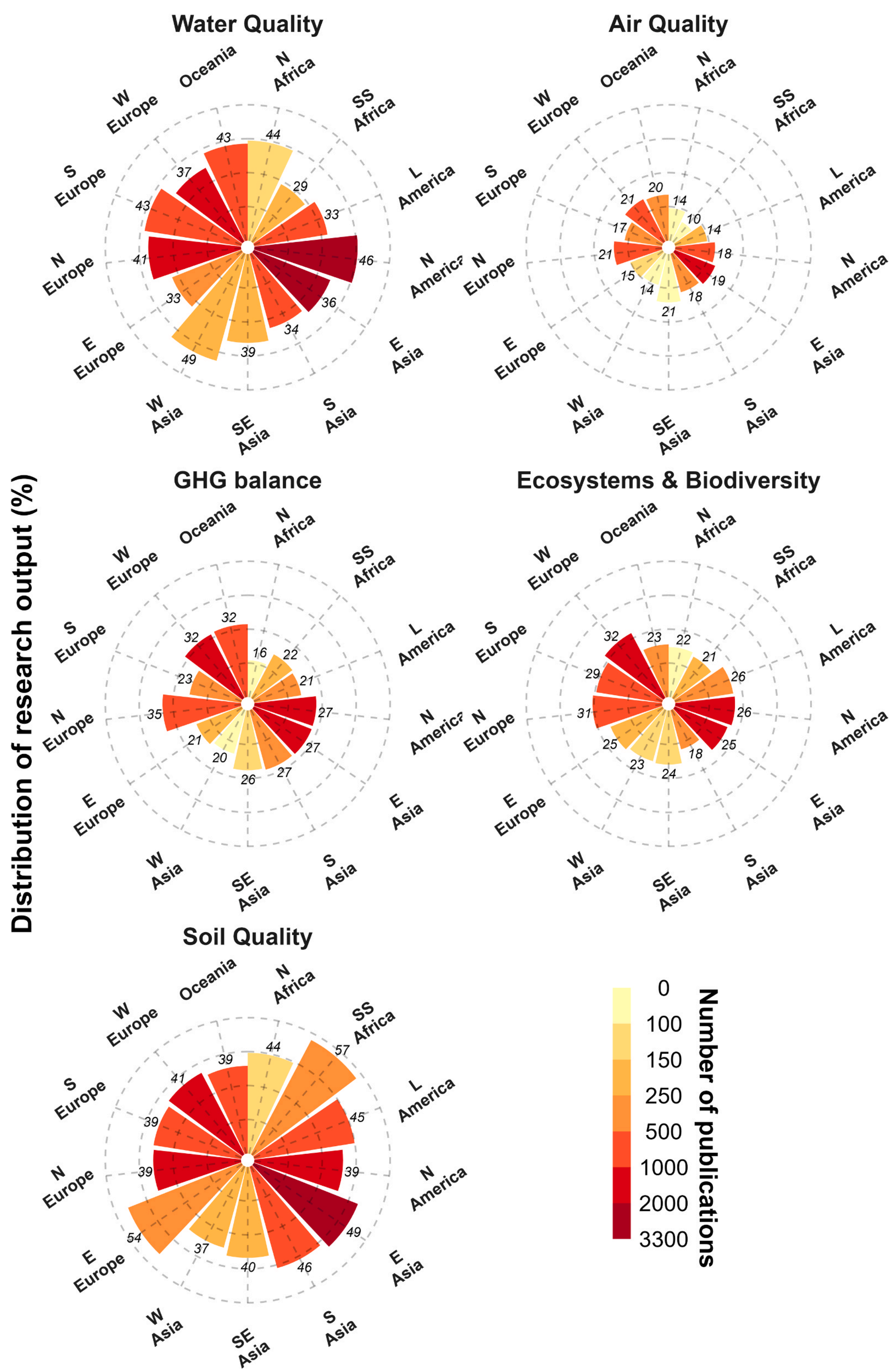

Fig. 1. Distribution of the number of publications, and respective fraction, per macro-region (n = 13) and N threat. Each dashed line represents a 15 % increment in the fraction of publications focussed on a given threat. Note that the total share may exceed 100 % as some publications address multiple N threats.

estimating the correlation strength using Spearman's correlation coefficient (see Section 2.5). We used the number of publications per unit of N surplus as a proxy of "research intensity" (Aguilera et al., 2021). This analysis was performed at the regional (Fig. S3) and national levels, but also across income and NUE groups.

2.5. Descriptive and statistical analyses

We performed a descriptive analysis using the average, standard deviation, coefficient of variation (CV) and interquartile range (IQR). We calculated the number of publications per N threat at a regional ($n = 13$) and country ($n = 142$) scales. We calculated scientific collaborations as the number of unique countries participating in a publication. We also quantified the fractional research efforts per N threat, as the ratio of the number of publications per N threat and to the total number of publications for a given region and country. These data were further disaggregated by income and NUE categories. Lastly, we estimated the number of N threat publications per funding source and research institutes based on authors' affiliations and country of residence. Individual funding sources were also grouped into broader categories (see Supplementary Methods). While a single publication can contain multiple countries/regions, funding sources and institutions, each unique occurrence was counted as one.

To identify significant regional differences in publications, we used the non-parametric Kruskal-Wallis test, reporting the chi-squared ($\chi2$), degrees of freedom and number of observations. We used a non-parametric approach due to the non-normal distribution and heteroscedasticity of the bibliometric data, which violated the assumptions of parametric tests. We also conducted a Dunn test post-hoc to identify for pairwise comparisons between regions. Pearson's correlation coefficient (r) was used to evaluate the linear correlation at 95 % significance between the regional research output and the N surplus. We adjusted p-values using the Bonferroni method to correct for type II errors.

3. Results

3.1. Regional assessment of N threat research

Our dataset revealed 20369 publications on N threats between 1990 and 2023, exponentially increasing at an annual rate of 12 %, from 10 publications in 1990–2149 in 2023 (Fig. S5). Our dataset revealed Soil as the most focussed N threat ($n = 8830$), followed by Water ($n = 8350$), Ecosystems & Biodiversity ($n = 5261$), GHG balance ($n = 5239$) and Air ($n = 3519$). The majority ($n = 12549$) of these publications addressed only one single threat, with equal proportions for Water and Soil (38 %), followed by Ecosystems & Environment (12 %), GHG balance (10 %) and Air (1 %).

Only 58 publications (<1 %) addressed all five WAGES threats simultaneously, while 5415 addressed two threats and 2340 three or four. The largest research overlap was between Air and GHG balance ($n = 2600$). Other overlaps, such as Soil and Water ($n = 1849$), Air and Ecosystems & Biodiversity ($n = 1586$), and Soil and GHG balance ($n = 1498$) obtained a similar importance (Fig. S4).

Fig. 1 shows the distribution of publications per N threat for each region with the highest number recorded in Eastern Asia ($n = 6678$) and Northern America ($n = 5057$), followed by Western- ($n = 3305$) and Northern Europe ($n = 2702$) (Table S2). In contrast, regions such as Northern Africa, Southeast Asia and Sub-Saharan Africa had substantially fewer publications, ranging from 308 to 769. We detected different temporal trends across all regions concerning the emergence of N threats in scientific agendas (Fig. S5). N threat research began to gain momentum first in North America and Europe (1990s) and in Oceania and Latin America (2000s). The early 2010s saw an exponential increase of N threat research in Eastern Asia and other regions in the continent, but also in Eastern Europe and Sub-Saharan Africa.

We identified differences regional differences in how research was allocated across N threats ($\chi2(4,\ n_{obs}{=}65) = 52.2,\ p < 0.0001$). Research on Soil and Water dominated, with median shares of 41 % (IQR hereafter: 39–46 %) and 39 (34–43 %), respectively. These were higher than the remaining three threats (all below $p < 0.01$; Fig. S6). For instance, research on Air (18 %; 14–20 %) received less than half of the fractional efforts relative to the quality of Soil and Water.

We found that regions with more publications showed lower variability in research distribution across N threats ($r = -0.52$), although this relationship was not statistically significant. These regions therefore tended to have a more even research distribution across all threats. Countries in Northern- and Western Europe showed the least variability in research distribution (CV: 23 %), while Northern- and Sub-Saharan Africa showed the greatest discrepancies (CV>53 %). Regions with fewer publications (and higher variability) tended to concentrate their efforts on Soil, often at the expense of the other compartments. Eastern Asia had the highest number of publications, focussing on Soil ($n = 3302$) and Water ($n = 2422$), while the lowest was for Air research in North Africa ($n = 44$).

3.2. Spatial variation of N threat research

The spatial distribution of research on N threats at the national level between 1990 and 2023 was highly heterogeneous (Fig. 2). Our dataset revealed that 50 % of the countries had 35 or fewer publications on at least one N threat. There was a large gap between bottom and top producers in terms of scientific output. The bottom 10 % of countries published three or fewer publications, while the top 10 % produced at least 748 publications. The distribution of research focus mirrored the regional trends, with Soil obtaining the highest median of 47 % (38–64 %), followed by Water at 39 % (30–50 %), GHG balance at 26 % (19–34 %), Ecosystems & Biodiversity at 25 % (20–32 %) and Air at 18 % (13–23 %). There was also a weaker but statistically significant inverse relationship between total research output and variability in N threat research ($r = -0.37$; $p = 0.004$). Research efforts in the top 10 % of countries were more homogeneously distributed across threats (CV: 31 ± 9 %) compared to other countries (CV: 56 ± 23 %).

China led N threat research, producing 6034 publications, which accounted for 90 % of the research output in East Asia. The United States of America (USA) followed with 4074 publications, representing 81 % of total publications in North America. Other major contributors included Germany, the United Kingdom, France, Spain and Italy in Europe ($n = 833$–1404); Canada ($n = 1158$) in North America; Australia ($n = 1135$); Brazil ($n = 922$) in Latin America and India ($n = 872$) in South Asia. Brazil and India emerged as the key research hubs in their respective regions, contributing to 59 and 55 % in their regional publications, respectively.

The top 10 % of countries in terms of publications generally followed the global trend, focussing on Soil or Water. However, others deviated from this pattern. For instance, the Netherlands prioritised Ecosystems & Biodiversity (43 %), a trend also identified in Denmark and France (36 %). GHG balance was the most researched N threat in the United Kingdom (40 %), while it was also important in Germany (36 %) and Australia and Canada (33 %). Countries with smaller research output (<10 publications) were predominantly clustered in Sub-Saharan Africa, Southeast Asia and Latin America, and prioritised Soil research. We identified 81 countries with no publications, primarily in Latin America ($n = 25$), Sub-Saharan Africa ($n = 21$) and Western Asia ($n = 5$).

3.3. Research according to income and nitrogen use efficiency

Fig. 3 shows the aggregation of research performance for each country, categorised by income level and NUE across N threat. The majority of low- (52 %) and lower-middle income countries (45 %) fell within the desired NUE range. In contrast, upper-middle and high-income countries showed a distinct pattern with 51 and 62 %, respectively, achieving a very low NUE. Countries with very high NUE,

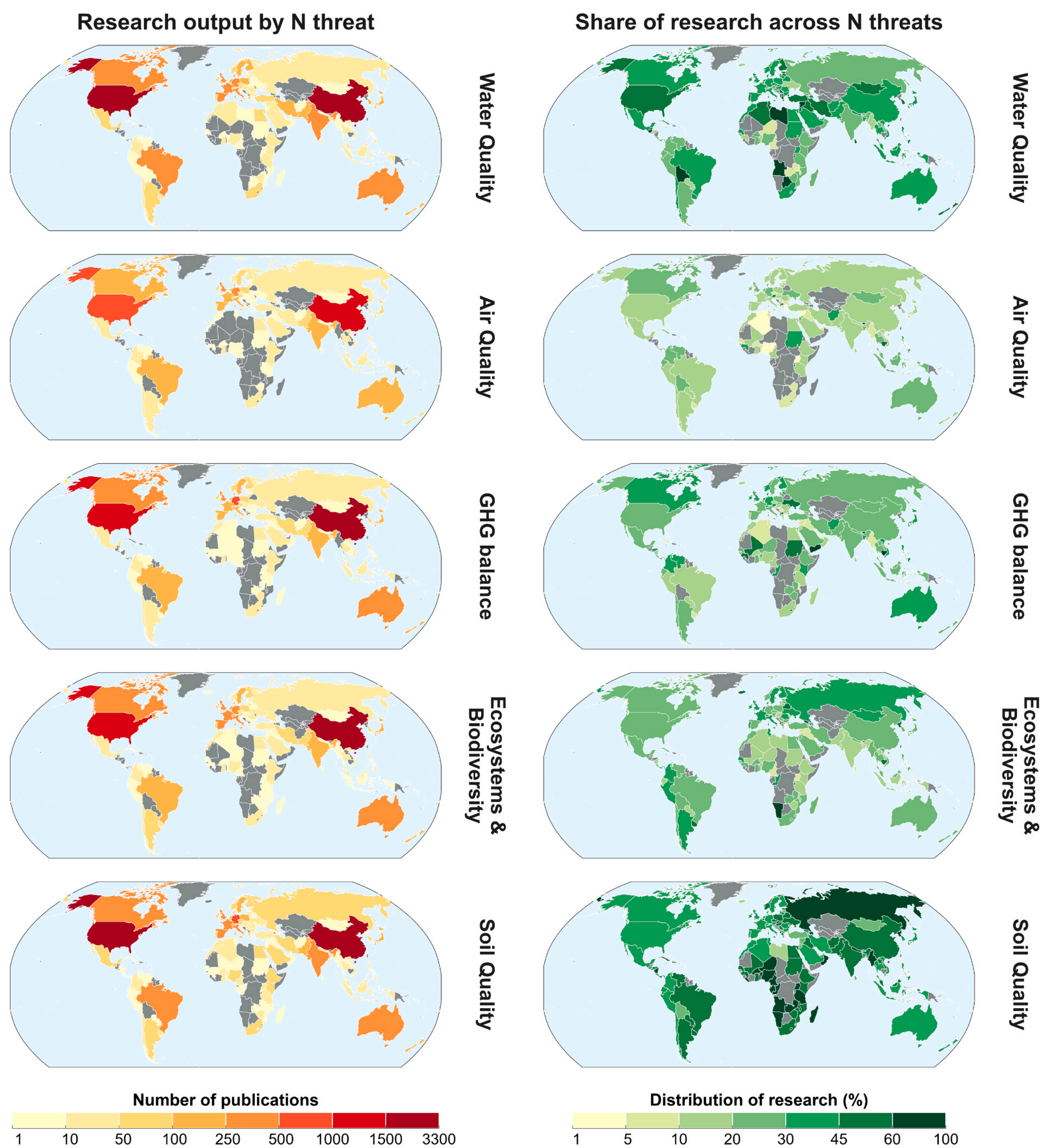

Fig. 2. Spatial variation of research at the national level for each N threat during the period 1990–2023 in terms of total publications (left) and fraction of publications (right). Fraction of publications were calculated as the number of publications for a given N threat relative to total publications.

indicative of soil N mining, were predominantly low- and lower-middle income countries. As income level increased, so did research output, with low-income countries producing 452 publications, lower-middle income countries 1875, upper-middle income countries 5483 and high-income countries accounting for 11429 publications. The distribution of publications according to NUE indicated that 9367 (50 %) publications were from countries with a desired NUE and 9166 (49 %) were from those with a very low NUE. Only 338 (1 %) were from countries with a very high NUE. We detected significant differences of N threat research according to income and NUE groups (Fig. S8).

Very low N efficiency. In countries with very low NUE ($n = 9166$), research efforts from high- ($p = 0.001$) and upper-middle income ($p = 0.03$) countries were higher than those with a low income, accounting for almost 85 % of all publications. Of the 51 low-income countries in this category, only 14 contributed to 214 publications or about 1 % of research. High-income countries published slightly more on Water than Soil, a pattern similar to low-income countries but with a much lower output. This contrasts with upper- and lower-middle income countries where Soil was prioritised over other threats.

Desired N efficiency. In countries with desired NUE values ($n = 9367$), high-income countries published more than low- ($p = 0.001$) and lower-middle income countries ($p = 0.02$), by a factor of 29 and 20, respectively. High-income countries contributed to 7338 publications or 78 % of all publications within this NUE category. Despite having fewer countries, this was 70 % higher than upper-middle income countries. Conversely, low and lower-middle income countries published less than those with a very low NUE by a factor of 4 although both included comparatively more countries. The variation of research

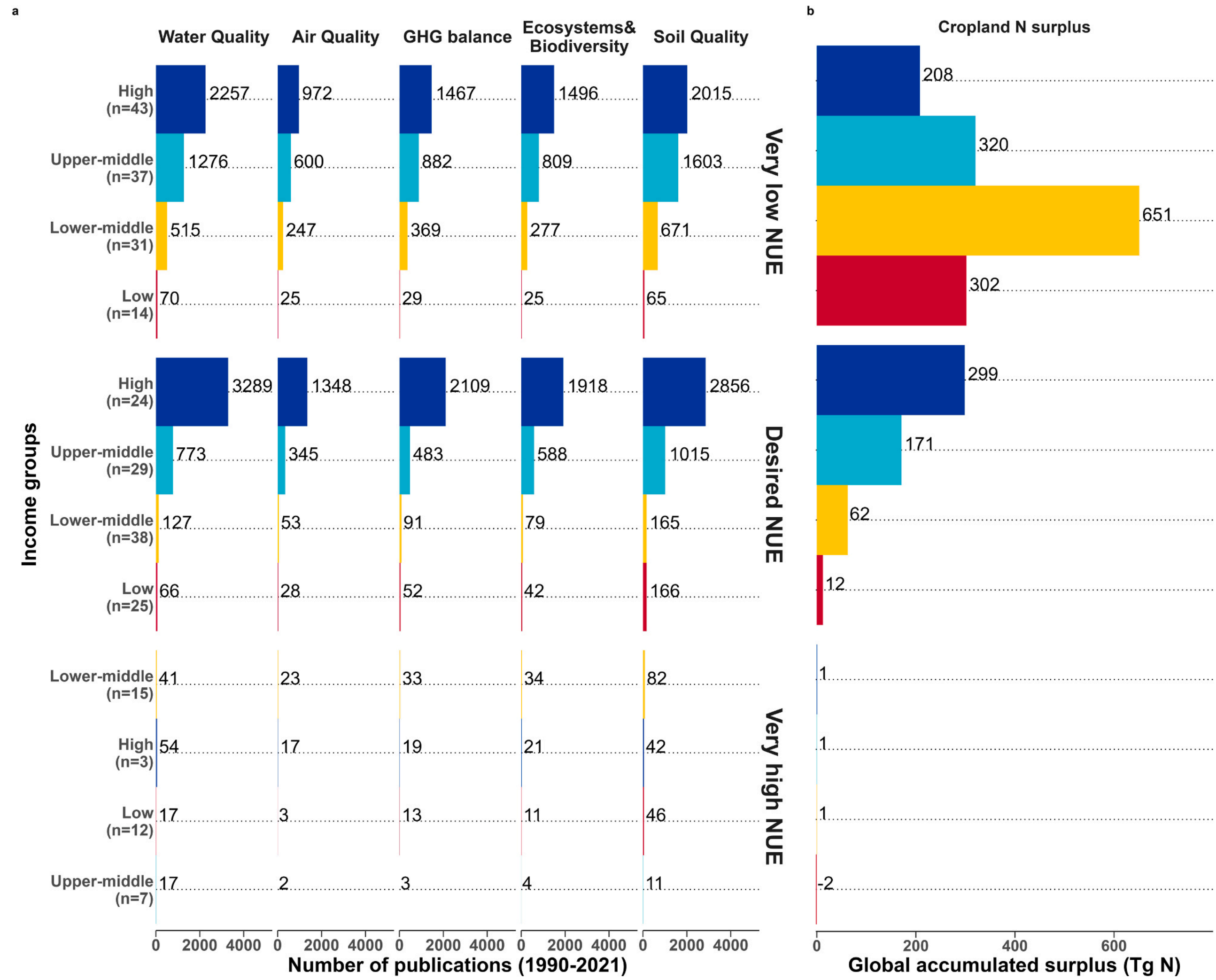

Fig. 3. (a) Total publications per N threat for each income group (low, lower-middle, upper-middle and high) and NUE category (very low: <50 %, desired: 50–90 % and very high: >90 %) for the period 1990–2021. The number of countries for each group is also identified in the vertical axis. Note it is possible that a country belonged to different classifications across the period due to developments in income and/or NUE. (b) Cumulative N surplus aggregated per income and NUE categories for the period 1990–2021. A detailed description of the distribution of countries per income and NUE groups is provided in the supplementary material.

per N threat deviated in some cases from the patterns identified in very low NUE countries in some cases. High income countries published more on the GHG balance than Ecosystems & Biodiversity while the opposite was true in upper-middle income countries. Additionally, there was a much greater emphasis on soil research in low NUE countries (n = 166 or 65 %).

Very high N efficiency. Countries with a very high NUE (n = 338) produced the lowest output out of all NUE categories, less than 4 % compared to countries with a very low or desired NUE. Only three high-income countries (Australia, New Zealand and Argentina) contributed to 104 publications over a span of fourteen unique years. Lower-middle income countries published 148 or 43 % of the publications, which was higher than those from upper-middle income ($p = 0.02$). These countries prioritised soil research, accounting to 55 and 44 % of their research.

Linkage with N pollution. There were marked differences between N research and cropland N surplus per income and NUE levels (Fig. 4). We estimated that 74 ± 8 % (46 ± 13 Tg N yr^{-1}) and 26 ± 8 % (17 ± 8 Tg N yr^{-1}) of the global N surplus came from very low and desired NUE countries, collectively corresponding to 99 % of N threat research. Low- and lower-middle income countries also had a disproportionately higher N surplus relative to N threat research. These countries were responsible for 19 ± 21 and 32 ± 19 % of global annual N surplus, collectively 51 ± 18 %. However, they produced only less than 1 % and 7 % of N threat publications, respectively. Countries with higher income and a very low NUE contributed less to the global N surplus but were the main contributors within countries with a desired NUE. Regardless, they accounted for 46 and 41 % of N threat research, respectively. Countries with very high NUE did not contribute meaningfully to research nor the global N surplus.

3.4. Regional correspondence between research and N threats

Research correlated well with the magnitude of N surplus, but to a varying degree across all N threats (Fig. 4). Overall, the N surplus was strongly and significantly correlated with research ($r = 0.69$, $p = 0$) but explained just under half of the variability (R^2=0.47). Research showed robust but often marginally significant positive relationships with N inputs for almost all N threats, especially for Air ($R^2 = 0.60$; $r = 0.80$), but not for Water.

We found that research intensities were 21 ± 18 (Soil), 19 ± 18 (Water), 13 ± 12 (GHG balance), 12 ± 10 (Ecosystems & Biodiversity) and 8 ± 8 (Air) publications per kg N ha^{-1}. North America and Oceania had a strong focus on Water and Soil Research, with 64 and 55 publications arise for each kg N ha^{-1} lost, respectively. Indeed, by removing

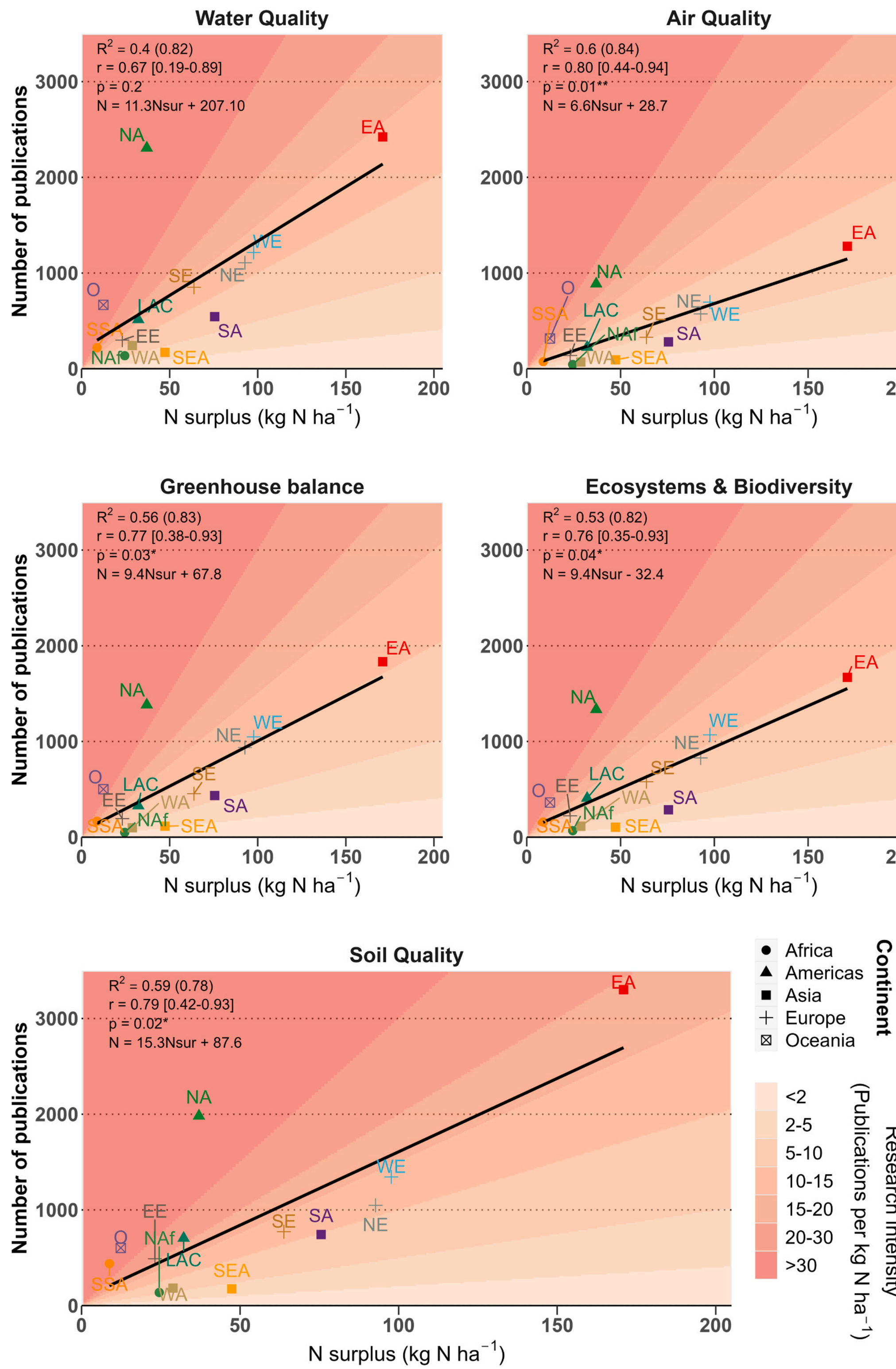

Fig. 4. Relationship between N threat research (N) and N surplus per region (n = 13), and number of publications per N surplus (kg N ha^{-1}). We averaged the N inputs from FAOSTAT for the period 1990–2021. These correspond to the difference of N inputs (sum of N fertiliser, manure excretion, seeds, atmospheric deposition and N fixation) and N removed in harvested products. Pearson correlation coefficient (r) (±95 % CI) was also calculated. P-values were adjusted using the Bonferroni method (n = 13). Significance was denoted as: * $p < 0.05$ and ** $p < 0.01$. Abbreviations are as: Asia (EA – Eastern Asia, WA – Western Asia, SEA – Southeastern Asia, SA – Southern Asia), Europe (NE – Northern Europe, SE – Southern Europe, WE – Western Europe, EE – Eastern Europe), Americas (LAC – Latin America and the Caribbeans, NA – Northern America), Africa (SSA – Sub-Saharan Africa, Naf – Northern Africa) and Oceania (O).

North America from the regression models, the correspondences increased by 56 ± 26 %, up to 105 % on Water and down to 20 % on Soil. Consequently, the N surplus would show a very strong correlation with research ($r = 0.84$; $p = 0$), explaining 70 % of the variability in the remaining countries.

Sub-Saharan Africa strongly focussed on Soil, with 53 publications for each kg N ha^{-1} lost. Despite obtaining the highest number of publications, Eastern Asia contributed with a median of 11 (9−14) publications per annual N surplus, which is in line with the median of all countries (10 publications per annual N surplus). Similarly, North- and Western Europe showed high surpluses with a high research output. Other regions produced fewer publications with respect to the average N surplus. Northern Africa (2–6 publications per kg N ha^{-1} of surplus), Southeastern Asia (2−4) and Western Asia (4−7) all obtained a median lower or equal than 4 publications per unit of N surplus. Southern Asia (2−5) also produced fewer publications, but the N surplus was comparatively higher in this region (75 kg N ha^{-1}).

We next explored the correspondence of N threat research and N surplus for each country per region and according to NUE and income levels (Table S3-4; Fig. S9-10). Only Northern African countries showed a significant correspondence in Soil ($p = 0.01$), Water ($p = 0.01$) and Ecosystems & Environment ($p = 0.03$) research, with the N surplus explained 85–92 % of the variability in research. We also detected a significant correlation in upper-middle- and low-income countries with a desired NUE in all five and two threats, respectively. In the former, the N surpluses explained 79–93 % variance in N threat research (all $p < 0.001$). In the latter it explained 61 % and 83 % of the variance of Soil and Air research (both $p < 0.01$). These were scattered across Latin America (e.g., Brazil), Eastern Asia (China), Western Asia (e.g., Turkey) and Eastern Europe (Russia). The remaining categories all showed non-linear relationships ($R^2 \approx 0$), with some even obtaining negative slopes.

3.5. Scientific, institutional and funding contributors

Scientific collaborations on N threats showed substantial regional disparities in research intensity and partnerships (Fig. 5a). European countries emerged as leading hubs, driving international collaboration across all N threats. These countries also had the largest internal collaboration, ranging from 3302 publications in Air to 6292 in Water. Despite smaller in volume, Europe played a key role in collaborations with Africa, contributing 27–41 % in all threats, particularly in Air and GHG balance. European collaborations in these threats also extended to Latin America and Oceania (~22 %), and Asia (~17 %), also with a similar contribution to Ecosystems and Biodiversity.

The USA and China were also important hubs for scientific collaboration on N threat research, albeit to a lesser extent than Europe. China accounted for 16–19 % of collaborations in Oceania in most threats, except for Water (10 %), and contributed 13 % of collaborations of the USA in Air and Soil (13 %). Notably, internal collaborations within China ($n = 1220–3832$) and the USA ($n = 640–2444$) represented the largest share of their respective partnerships, comprising 59–74 % and 53–73 % of their collaborations, respectively.

Regions with smaller research volumes, such as Africa, Oceania, and Latin America, show distinct patterns in their relative contributions. Africa showed a stronger relative focus in Water and Ecosystems and Biodiversity, while Oceania demonstrated balanced contributions across threats. Latin America's collaborations were tied to Europe but were generally less prominent across N threats. Air and GHG Balance remained relatively low in collaboration volumes.

We identified the top institutions in terms of N threat research (Fig. S11) and funding sources (Fig. 5b). The top universities were predominantly from China ($n = 9$), Europe ($n = 3$), USA ($n = 3$) and Australia ($n = 1$). These contributed to 8.4 ± 2.4 % of N threat publications, ranging from 5.9 % on Air to 12.2 % on Soil.

There were two main groups of institutions according to N threat research: (i) generalists, where research was evenly spread across threats and (ii) specialists which emphasised a particular environmental compartment. Generalists, such as the Chinese Academy of Sciences, China Agricultural University or Wageningen University, were the main knowledge hubs across all threats. For instance, the Chinese Academy of Sciences published 3–6 % of all publications across the different N threats. On the other hand, specialists like the Institute of Atmospheric Physics and the University of Florida tended to focus on a single N threat (air and water, respectively).

The bulk of research was funded by two main types of funding sources irrespective of region and N threat. Strategic initiatives and foundations funded 38–49 % and 26–35 % of all publications per N threat, respectively. Universities and Institutes showed a consistent funding contribution to N research (20–22 %), while councils (9–15 %) and ministries (10–13 %) obtained a comparable importance across all threats. The remaining types of funding sources had a relative contribution consistently below 7 % of publications. We note how the industry & private sector funded only 2–4 % of research published in scientific journals.

We also explored the most relevant individual funding sources (Fig. S12). The National Natural Science Foundation of China was the largest contributor with 23–27 % of global publications. The remaining most important funding sources were predominantly from China (e.g., National Key R&D Program of China; 8–11 %). Some funding sources were from elsewhere, such as the USA (USDA National Institute of Food and Agriculture; 2–4 %), European Union (2–4 %), the United Kingdom (e.g., Natural Environment Research Council; 2–3 %) and Brazil (National Council for Scientific and Technological Development; 2–3 %).

4. Discussion

4.1. Research in line with N threats

We found a strong overall correlation between the cropland N surplus, used here as a proxy for the severity of N threats, and N threat research at the regional level (Fig. 4). However, the extent to which research output increased with the N surplus varied markedly across regions. Regions with high surpluses tended to publish more on N threats (Research-intensive), but these may not necessarily translate into immediate mitigation efforts and observable improvements in the ecological status of ecosystems (Klages et al., 2020). In other cases, low research output may not reflect low threat severity, but rather a limited scientific capacity or weak uptake of available knowledge (Research-constrained).

North America and Oceania emerged as research-intensive, with a research intensity over 43 and 40 publications per kg N ha^{-1} lost across all threats, respectively (Fig. S13). This was well above what would be expected based on N pollution levels. Conversely, South Asia was the most research constrained: while its research intensity was moderate (5–10 publications per kg N ha^{-1} lost), it accounts for 29 % of the global N surplus but contributes only with 8 % of publications. This demonstrates an existing substantial gap between the severity of N threats and research in this region or the actual implementation of research findings in policies and fertiliser practices applied.

We detected an overall lack of predictive power from the N surplus, explaining less than half of the variability in research. This points to the existence of external drivers (Zhang et al., 2015), such as economic capacity, political priorities, environmental awareness and institutional infrastructure. These structural constraints help explain why lower income nations tend to prioritise Soil research, driven by chronic soil fertility limitations, whereas higher income regions, with stronger institutional and monitoring capacity, distribute research more evenly across Water, Air, GHG and Ecosystem threats linked to intensive fertiliser use.

Even so, research aligned reasonably well with the severity of specific threats in several African countries (Fig. S9) and in upper-middle and low-income countries with desirable NUE (Fig. S10). This suggest

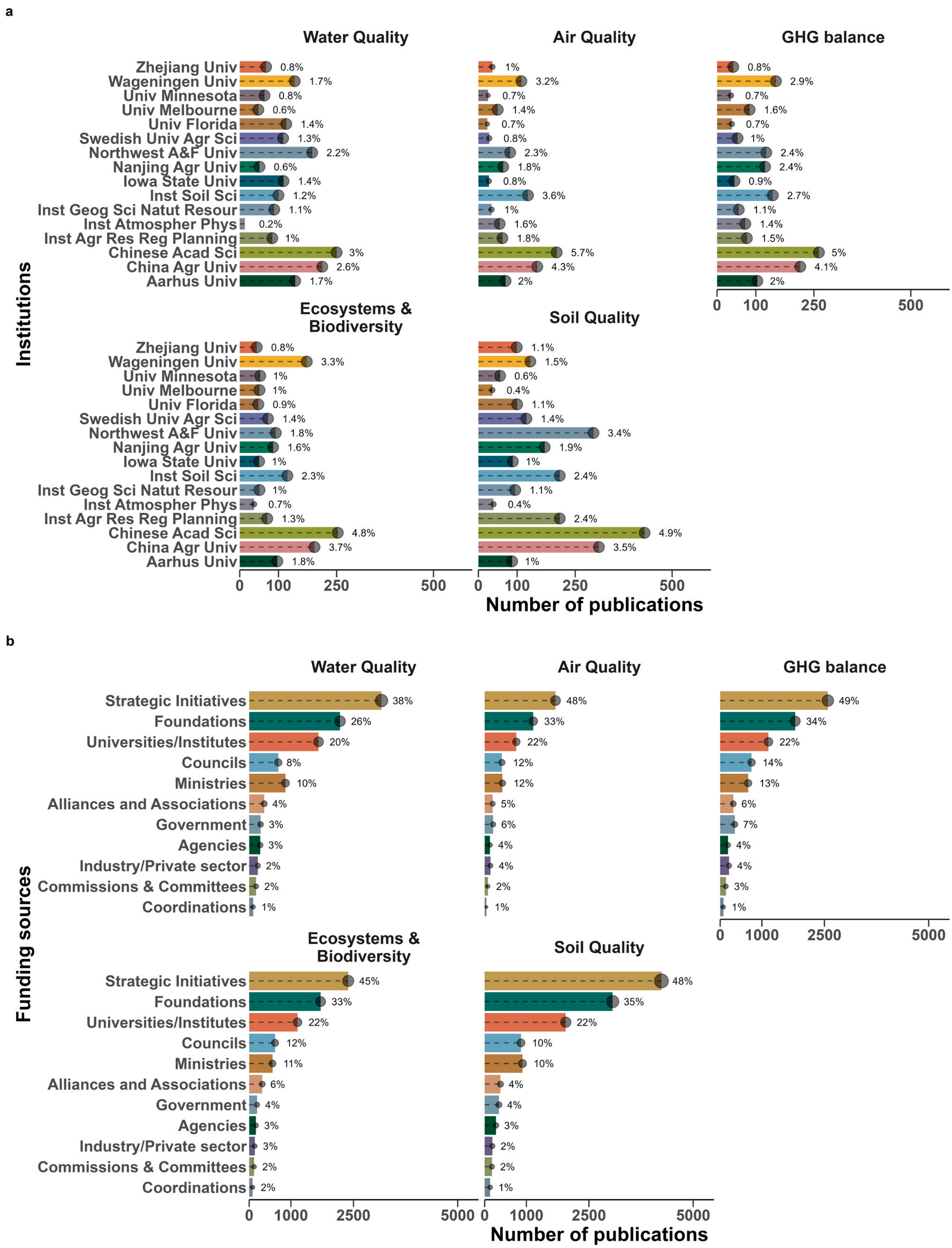

Fig. 5. (a) Scientific collaborations during 1990–2023 across all five N threats. The role of China and the United States of America are also highlighted. (b) Most important types of funding sources of N threat research – Fig. S10 shows the regional allocation of funding sources. Percentage represents the fraction of publications across each N threat. Strategic Initiatives refer to programmes, projects, initiatives or schemes.

how some regions may be efficiently channelling research efforts to address their most pressing N threats. In most regions, however, research appears to be disconnected from environmental threats, indicating that other factors are likely influencing regional priorities.

4.2. Drivers of regional research priorities

The research landscape showed marked regional and national differences. The top two producers, China and the USA, accounted for 46 % of all publications, with North- and Western Europe adding to a total of almost 70 % from only 19 countries. By contrast, the bottom 10 % of countries, mostly in Africa and Latin America (Fig. 3), produced less than the top countries by two orders of magnitude.

These imbalances were also evident in how countries distributed research across N threats. Higher income nations tended to maintain a more balanced focus across multiple N threats. Greater pro-environmental awareness (Zhang et al., 2021), more financial resources (Kummu et al., 2018), higher levels of institutional development (Fig. 6a) and technological infrastructure to monitor air and water pollution are likely enabling, or even a pre-requisite, of multi-compartment N management studies. Wealthier nations also operate within international regulatory frameworks that require a broader approach to N management, such as the European Union's Water Framework Directive and the National Emissions Ceilings Directive. This leads to more stringent policy requirements and societal expectations in ensuring a minimal impact of N threats from agriculture. This is illustrated by the Netherlands, where concerns about atmospheric N deposition (Erisman, 2021) have triggered research efforts to support policy and reduce N losses from agriculture (van Selm et al., 2023).

Our data showed that Soil dominated the research portfolios in countries with lower research output, mainly with low- and lower-middle income countries, whereas higher income countries distributed their efforts more evenly. This reflects differences in the knowledge, equipment and institutional capacity required to monitor each threat. Soil research dominates in countries with limited resources because it is cheaper, more accessible and directly tied to food production. Conversely, Air quality requires specialised equipment and expertise to quantity gaseous N losses. Chronic soil fertility issues and limited monitoring capacity reinforce this focus, making soil the most practical, and arguably cost-benefit, entry point for N research in low-income settings.

Countries focusing on Soil are often struggling with declining soil fertility (Fig. 2), jeopardising food production and food security (Kopittke et al., 2019). Low soil fertility contributes to chronic poverty in farming communities (Barrett and Bevis, 2015), creating poverty traps (Tittonell and Giller, 2013). Limited research capacity and funding, lower levels of institutional and technological development constrain the feasibility of conducting multi-compartment research. These constraints are compounded by gaps in environmental monitoring, including limited inter-agency cooperation, lack of monitoring equipment or technical expertise to operate it. As soils play a critical role in agricultural productivity, influencing both environmental impacts and the potentials to reduce them, it is often the most targeted N threat. Thus, prioritising soil research can be seen as a pragmatic response to the most pressing N threat in lower income countries, where food security takes precedence over environmental concerns.

By integrating bibliometric data with cropland N surplus across the WAGES framework, our analyses provide a new diagnostic perspective that points to where research attention diverges from the severity of N threats. These differences highlight opportunities for low hanging fruits, where targeted research can simultaneously improve food security and reduce environmental N losses.

4.3. Low-hanging fruits

Our study reveals a research gap in low- and lower-middle income countries with very low and very high NUE (Fig. 3). These represent the "too much" and "too little" paradigm of regional N availability (Schulte-Uebbing et al., 2022), respectively. They are also low-hanging fruits where strengthening N research can drive major progresses in both food security and environmental management. Supporting research in these countries may also help avoid the historically N mismanagement observed in many high-income countries (Ludemann et al., 2024). However, this requires the prioritisation and adoption of new research findings in agricultural practices.

Existing bottlenecks (Dobermann et al., 2022) must be tackled to enhance the adoption of new management practices. "Too much" countries offer the greatest potential to reduce N pollution by adjusting N inputs while maintaining crop yields (Figs. S14-15), which requires substantial progress in increasing NUE. In "too little" countries, food security can be improved by increasing N inputs and food production (Figs. S16-17), which may initially reduce NUE from soil mining to more sustainable levels.

Achieving a desired NUE while maintaining crop productivity requires an efficient allocation of N inputs to avoid an excessive increase in N surpluses (Mueller et al., 2017). Conceptual frameworks have demonstrated how redistributing synthetic fertiliser (Smerald et al., 2023) and manure (Devault et al., 2024) from "too much" to "too little" regions could improve food security and mitigate pollution while staying within environmental limits.

Further closing regional N cycles will depend on integrating nutrient-recycling options within food systems, including organic waste recycling, optimized manure use and nutrient recovery from wastewater (Kahiluoto et al., 2024). By identifying where research efforts differ from the severity of N threats, we provide a basis for prioritising circular N strategies in the regions where they would yield the greatest environmental and food-security benefits.

4.4. Challenges of research imbalances

Several caveats need to be considered when interpreting our findings. First, we focussed on the absolute number of publications over the last three decades. This overlooks large differences in country populations, which can hide how strongly individual countries invest in N research. When publication counts were normalised by population (Fig. 2), the research landscape shifted, with Canada, Oceania and Northwest European countries dominating instead of China and the USA (Fig. S18). This suggests that the high publication totals in parts of Asia reflect, at least partly, their large populations and land areas rather than a proportionally greater investment in N research.

Normalising by population therefore provides a more equitable basis for comparing national research contributions. However, population is only a proxy for research capacity. A more precise normalisation would account for the size of national research workforces, although such data are not yet consistently available. More importantly, we were unable to quantify the quality or local impact of research outputs. Even where substantial research exists, turning knowledge into practice remains a challenge (Mehrabi et al., 2020).

Second, we identified that relatively few publications addressed multiple N threats. Less than 12 % of all publications jointly addressed at least three N threats together, and less than 1 % accounted all five. Agricultural and environmental challenges require an integrated approach that combines system analysis with the identification and adoption of N management measures. These also need to account for the risks of pollution swapping across environmental compartments. While the current findings are likely an artifact from the limited number of keywords in publications (usually five), which authors prioritise to the focus at hand, it has been evidenced how N policies lack integration across environmental compartments (Kanter et al., 2020).

Third, a substantial proportion of research in low-income countries relies on data, approaches and models developed in high-income countries, a finding that has also been made regarding research on sustainable livestock development in low- and middle-income countries (Paul et al., 2021). Low-income countries therefore need support so that research addresses both food security and environmental N impacts.

Fourth, we found a large concentration of research in a small number of countries, institutes and funding sources (Figs. 2 and 3). This increases the risk that research reflects the priorities of a few actors rather than national or local needs. This dependency on few key players makes the global research landscape highly vulnerable to changes in political priorities. This is illustrated by a shift in political (Rodrigues, 2021) and scientific policies (Oliveira and Todeschini, 2024) in Brazil, which may jeopardise scientific development. The integration of global policy instruments could help somewhat alleviate this over-reliance, ensuring stability in N research.

In addition, several methodological limitations should be acknowledged. Using only the Web of Science database may have introduced a coverage bias, potentially underrepresenting publications in non-English languages or those published in non-indexed regional journals. There is also a time lag between article acceptance and indexing, which may underestimate publication data for recent years. More importantly, while the number of publications is a proxy for research intensity, it does not consider research quality, knowledge uptake or policy relevance.

4.5. Collaborative global solutions as the way forward

Addressing regional gaps in N research and management requires coordinated international efforts (Morseletto, 2019). The concept of an "International Nitrogen Management Systems" has been developed to harmonise both the research and policy landscapes, while setting priorities according to regional N-related issues (Sutton et al., 2020). Such a system could help rebalance the skewed and concentrated research landscape. A prerequisite for effective coordination is a clear understanding of how research efforts vary across regions, particularly the regional severity of each WAGES threat.

Achieving this goal demands collaboration involving the scientific community, policymakers and local stakeholders to ensure a just and sustainable N management. Equally important is building transdisciplinary research platforms that bring together soil science, atmospheric chemistry, ecology, social scientists and agronomy. This is crucial to co-develop local solutions that reflect the complexity of N pollution.

To be effective, these efforts need to ensure that successful knowledge is transferred from research-intensive to research-constrained regions through international collaboration, capacity strengthening and technology transfer. Strengthening these knowledge flows can also help direct support to address scientific constraints through international research and development programmes, including CGIAR, the Global Environmental Facility and bilateral development-aid initiatives. These actions would be valuable in overcoming research limitations, since insufficient research and limited awareness of sustainable N management practices can themselves be barriers to adoption (Masso et al., 2017).

However, knowledge transfer must go beyond technical support and capacity strengthening. In many low-income regions, research agendas are often shaped by donor priorities, Northern-led consortia, or even externally imposed through dynamics such as land grabbing (Liao and Agrawal, 2024). These may not reflect local environmental, social and economic conditions. For instance, donor-driven projects may carry goals that overlook local needs, while collaborations led by institutions in high-income countries can marginalise local actors. Additional structural barriers such as language, limited access to high-impact journals, institutional gatekeeping and uneven research funding further amplify inequities in participation and visibility within the global N research landscape.

While research integration is essential for understanding the complex and interconnected challenges of N management, implementation must remain regionally adaptable. The technical principles of integrated sustainable N management practices in agriculture are well established (Brownlie et al., 2024). Although N threats are highly site-specific (Cui et al., 2021; Van Damme et al., 2021), many practices are transferrable from one region to another. A bottom-up strategy, guided by the severity of N threats and local food security needs, can help overcome the existing barriers in the dissemination and application of feasible but sustainable practices. However, the key problematic in lower income countries may not be knowledge- or research-based, but one out of necessity as low input-low output cropping systems can be a rational solution to prohibitive social and capital costs (Barrett and Bevis, 2015).

Ensuring the principles of sustainable N management are equitably applied across regions remains a major sociopolitical challenge. Here, we aim to raise awareness to the role that the scientific community must play in not only achieving a desired N use efficiency, but also a desired knowledge use efficiency. Our study allows both national and regional research and policy coordinators to see to what extent their research effort is in sync with surrounding regions and the extent of N problems.

5. Conclusion

Here we provide the first integrated global assessment that links cropland nitrogen surplus with agricultural research outputs across the WAGES framework. Our analysis shows a strong correspondence between the number of publications on nitrogen threats and the severity of those threats, although there are marked regional differences in research outputs and scientific collaborations. The nitrogen surplus explains less than half of the variation in research outputs, highlighting the influence of socioeconomic, political and institutional factors in shaping the global research landscape.

We find a clear disconnection in lower income countries, which contribute over half of global nitrogen losses but produce only 8 % of all publications. These countries often prioritise soil research, reflecting immediate concerns with soil fertility and food production. Conversely, higher income countries have a more balanced research distribution across nitrogen threats. Investing in research-constrained countries offers an opportunity to address low-hanging fruits, improving food security while simultaneously reduce nitrogen pollution.

Addressing the global nitrogen dilemma will require international collaboration that supports local priorities and builds long-term human and institutional capacity. Enabling locally led research and increasing the visibility of contributions from research-constrained countries are important steps toward a more equitable and responsive nitrogen research landscape: one that better reflects the distribution of threats and helps deliver more effective and just nitrogen management.

CRediT authorship contribution statement

J. Mogollon: Writing – review & editing. **A. Sanz-Cobeña:** Writing – review & editing, Formal analysis. **C.S.C. Marques-dos-Santos:** Writing – review & editing, Formal analysis. **W. de Vries:** Writing – review & editing, Formal analysis. **M. Graversgaard:** Writing – original draft, Formal analysis. **K. Hayashi:** Writing – review & editing, Formal analysis. **M. Quemada:** Writing – review & editing, Formal analysis. **L. Lassaletta:** Writing – review & editing, Formal analysis. **E. Aguilera:** Writing – original draft, Formal analysis. **F. Giannini-Kurina:** Writing – review & editing, Formal analysis. **H.J.M. van Grinsven:** Writing – review & editing, Formal analysis. **G.H. Ros:** Writing – review & editing, Formal analysis. **T. Dalgaard:** Writing – review & editing, Formal analysis. **K. Butterbach-Bahl:** Writing – review & editing, Formal analysis. **J. Serra:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **J. Marinheiro:** Writing – review & editing.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT to check language clarity. All content was written, verified, and edited by the authors, who take full responsibility for the final work.

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2026.104312.

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