Gaps and opportunities in nitrogen pollution policies around the world

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Abstract

Nitrogen pollution is an important environmental issue gaining traction in policy circles. However, there is little understanding of current nitrogen policies around the world: whether they account for nitrogen's unique ability to exacerbate multiple environmental impacts or balance nitrogen's role as an essential agricultural input and major pollutant. Here we assemble and analyze the first database of nitrogen policies generated by national and regional legislatures and government agencies, a collection of 2726 policies across 186 countries derived from the ECOLEX database. The database covers all major environmental sinks (such as air, water and climate), economic sectors (including agriculture, wastewater and industry), and policy instruments (from market mechanisms to regulatory standards). We find that sink-centered policies are predominantly focused on water, mirroring the distribution of nitrogen's global environmental and human health costs. However, policy integration across sinks is severely lacking, which heightens the risk of substituting one form of nitrogen pollution for another. Moreover, two thirds of agricultural policies (ranging from broad sectoral programs to nitrogen-specific measures) incentivize nitrogen use or manage its commerce, demonstrating the primacy of food production over environmental concerns.

Nitrogen (N) pollution is a multifaceted and growing threat to the environment and human health. Human activities have doubled the scale of the N cycle since the industrial revolution, driven by increasing production and consumption of N inputs as global population and food demand per capita continue to grow[1,2]. The distinctive chemistry of the N cycle, which allows one N atom to cascade through a variety of compounds once in reactive form (any form other than atmospheric dinitrogen, N_2), means that N pollution exacerbates almost every major environmental issue, from air and water pollution, to biodiversity loss, stratospheric ozone depletion and climate change[3,4]. Today, humanity is considered to be in the high-risk zone of the N planetary boundary – a level of interference which has numerous immediate (e.g. air pollution) and long-term (e.g. climate change) consequences for the Earth System[2,5]. Moreover, its multiple forms impair humanity's efforts to return or remain within a number of other planetary boundaries, including stratospheric ozone depletion and climate change. Even proposed mitigation options for problems such as climate change could exacerbate N pollution – for example, biofuels could be a trivial or dominant source of nitrous oxide (N_2O), the third most abundantly emitted greenhouse gas, and thus offset a significant proportion of the purported climate benefits of biofuel production depending on what crop(s) predominate and the amount of land devoted to growing them[6]. N has thus become a major international environmental policy issue in its own right, with the United Nations Environmental Assembly (UNEA) calling for increased action in its Sustainable Nitrogen Management resolution (UNEP/EA.4/L.16) and the 2019 Colombo Declaration outlining the ambition of a 50% reduction in N waste by 2030[7].

However, there is very little sense of the current landscape of national and regional N policies around the world – how many there are, what sectors they cover, what issues they address, and what kinds of instruments they use. Even major N assessments over the past decade, from Europe to California to India, focus largely on analyzing sources and impacts of N pollution and provide limited insight into the policies in their specific regions[8-10]. More fundamentally, do N policies match our understanding of the dominant pollution sources, the environmental sinks most impacted, and the unique chemistry of the N cycle? And how do N policies reflect humanity's complex relationship with N as both an essential resource and major pollutant? What is the balance between policies that incentivize N use due, for example, to food security concerns, and policies that prioritize N pollution mitigation? This lacuna in our understanding of N policy is particularly notable given the mandate of the newly established UNEA Interconvention Nitrogen Coordination Mechanism to “better facilitate communication and coherence across nitrogen policies” (UNEP/EA.4/L.16) and the commitment of the Colombo Declaration signatories to “develop national roadmaps for sustainable nitrogen management”. For these efforts to be successful, an important first step is to establish a baseline understanding of the national and regional N policies currently in force around the world.

Consequently, we created the first database of national and regional N policies with global coverage. The policies are drawn from ECOLEX, the largest environmental law database in the world, with records of over 160,000 national, regional and international environmental laws (Methods). ECOLEX is an aggregation of the law holdings of the Food and Agriculture Organization of the United Nations (FAO), the International Union for the Conservation of Nature (IUCN) and the United Nations Environment Programme (UNEP). We identify and classify each N policy by country, instrument type, sector, sink and scale (Methods). Consequently, our unit of analysis is number of policies, which includes policy clusters: collections of policies linked by a common objective in one country or region counted as one policy (Methods). This database and the accompanying analysis could be a resource to policymakers developing comprehensive national roadmaps for sustainable N management: helping them understand what existing policies can be harnessed and what gaps need to be filled. Such roadmaps could help the international community meet its numerous climate and sustainable development commitments[13].

Results

We identified 2726 N policies currently in force across six continents, 186 countries, and all major environmental sinks and economic sectors. Table 1 defines the policy categories (adapted from the International Energy Agency’s Policies database and the NewClimate Institute’s policy database to the N context – Methods) and provides an example of each.

Policy category	Definition	Example *Country (Year): Title*	 *Description*
Regulatory	Quantifiable constraints on N consumption, production or loss	Australia (2013): Environmental Protection (Vehicle Emissions) Regulations	Vehicle emissions standards for nitrogen oxides (NO_x) with financial penalties for non-compliance
Economic	Financial incentives and signals to spur enforceable and quantifiable behavior change related to N	Mauritius (2004): Wastewater Regulations	Licenses for effluent discharge in wastewater, which include Total Kjeldahl Nitrogen limits
Framework	Broad objectives relevant to nitrogen pollution with no quantifiable constraints and/or delegation of authority for N policymaking to another governing body	Egypt (2016): Egyptian Biodiversity Strategy and Action Plan (2015-2030)	Broad objectives for biodiversity conservation including "control of fertilizers and pesticides".
Data & Methods	Data collection/reporting protocols, including parameters for Environmental Impact Assessments	Bosnia and Herzegovina (2011): Regulation on the manner of monitoring on air quality	Parameters for measuring air quality, including sampling, location and evaluation criteria. Lists nitrogen dioxide and ammonia among other pollutants.
R&D	Research and development funding into N pollution effects or mitigation technologies	Vietnam (2012): Decision approving the program on hi-tech agriculture development under the national program on hi-tech development through 2020.	State funding for public and private research into novel agricultural technologies, including enhanced efficiency fertilizers
Commerce	Regulation of commercial and trade activities surrounding N	Albania (2011): Law on the use of fertilizers	Rules on packaging, labelling, transport, storage, trading and registration of fertilizers
Pro-Nitrogen	Incentives to increase use of N	Kenya (2013): Crops Act	Programs to reduce fertilizer costs via, for example, private sector involvement in fertilizer importation and local fertilizer manufacturing.

Table 1 **Nitrogen policy categories and examples**. The seven nitrogen policy categories identified as part of this study with national examples. See Methods for more detail on each category.

Nitrogen policies by policy category

While policies from each category listed in Table 1 can play an important role in N pollution, certain policies are more likely to lead to measurable reductions in N pollution than others. We therefore classify policies that set quantifiable and enforceable constraints on N production, consumption (which includes farmer application of agricultural N inputs) and loss as “core” N policies – calculated in our database as the sum of economic and regulatory policies (Table 2). Constraints in this context can range from ambient pollution standards and emission limits to fertilizer taxes and water trading markets. There are 1134 core N policies, constituting 42% of the total. Examples of core N policies include nitrate (NO_3^-) concentration standards in the European Union’s 1991 Nitrates Directive – an ambient, water quality standard – and nitrogen oxides (NO_x) emission limits on large industrial facilities in Ukraine’s 2014 National Emissions Reduction Plan – a source-based, air quality standard.

936 additional policies are either framework (629), data & methods (291) or research and development (R&D) policies (16). Though these policies do not directly limit N pollution, they are important elements of the N policy universe. Framework policies represent the most diverse policy category, referring to policies that delegate authority for N regulation from one body to another and overarching environmental and agricultural policies that introduce broad objectives relevant to N (Table 1). An example of the former is Canada’s 1979 Meewasin Valley Authority Act, which creates the Meewasin Valley Authority in the province of Saskatchewan and gives it the power to enact a range of conservation measures, including agricultural buffer zones. An example of an overarching framework policy is Botswana’s 2016 National Biodiversity Strategy and Action Plan, which lists the development of “regulations to limit the use of various pollutants”, including fertilizers, as a required action to improve air, water and soil quality.

In contrast to policies related to N pollution mitigation, approximately 25% (656) of N policies in our database are commerce and pro-nitrogen policies, focused on facilitating or incentivizing N production and/or consumption. For example, Indonesia’s 2011 Regulation on Terms and Procedures for the Registration of Inorganic Fertilizer is classified as a commerce policy as it implements several quality standards for inorganic fertilizers, in part to “give business certainty in conducting producing activities, procurement and circulation of inorganic fertilizer." A 2009 Colombian policy establishes a program to provide coffee farmers with credit to purchase fertilizer and is thus considered a pro-nitrogen policy. The total number of commerce and pro-nitrogen policies in our database is likely a conservative estimate given that ECOLEX is an environmental law database and therefore these types of policies are not a primary focus. The balance between N mitigation and consumption is discussed further below in the context of agricultural policies.

Policy category		**Sink**		**Sector**		**Continent**	
Type	*Number*	*Type*	*Number*	*Type*	*Number*	*Type*	*Number*
Regulatory*	878	Water	669	Agriculture	942	Europe	971
Framework	629	Air	366	Waste	262	Asia	610
Commerce	472	Ecosystems	183	Industry	78	North America	384
Data & Methods	291	Climate	130	Transport	64	Africa	364
Economic*	256	Soil	14	Energy	32	South America	299
Pro-Nitrogen	184	Multiple sinks**	28	Multiple sectors**	35	Oceania	90
R&D	16						
Total	2726	**Total**	1390	**Total**	1413	**Total**	2726

Table 2 **Nitrogen policy breakdown by category, environmental sink, economic sector and continent.** Categories marked with asterisks ("*") are considered "core categories". Categories marked with double asterisks ("**") also include integrated N policies, which address multiple sectors and sinks of N pollution in a more unified approach. Certain policies can be classified by both sink and sector (e.g. a wastewater policy that focuses on water), but others only apply to either a specific sink or sector – hence the sum of sink and sector policies does not equal the total number of N policies.

Water dominates sink-focused policies

N policies focus on either an environmental sink or an economic sector (Table 2), with a small number covering both. Each sink and sector could be divided further into a number of sub-categories, for example inland and marine for water, livestock and crops for agriculture, and automobile and aviation for transport. However, the focus of this initial analysis is on the broader classifications listed in Table 2.

For sinks, water is the dominant focus (almost 50% of policies), followed by air, ecosystems and climate. The focus on water holds true for core N policies and mirrors the distribution of global environmental and human health costs associated with N pollution on water and air quality, ecosystem damage and climate change, suggesting that the current N policy landscape has internalized N pollution's most costly impacts relatively accurately (Figure 1). The major economic impacts of N-induced water pollution are increased eutrophication, declines in marine habitats and loss of recreational use, while the major air pollution impact is the increased incidence of respiratory diseases[14]. Together, these more local impacts outweigh the global impacts of N pollution from nitrous oxide's (N_2O) important role in climate change and stratospheric ozone depletion by a ratio of 50:1 in terms of economic damages[15] (Figure 1).

However, only 28 of the 1390 sink-focused policies address N impacts across multiple sinks – an approach at odds with the cross-cutting chemistry of the N cycle, where one N atom can have a variety of environmental impacts. And yet it reveals how most governments approach most environmental policy, which is to legislate by sink, i.e. air vs. water vs. climate[15]. For example, in the EU, NO_3^- pollution is controlled under the Nitrates Directive, while ammonia (NH_3) and NO_x emissions are subject to the EU National Emission Ceilings legislation. Meanwhile, N_2O reductions can generate credits from the EU Emissions Trading System (the world's largest carbon market), but only from certain industrial sources (and not agriculture).

A siloed approach to N policy is problematic in that it can incentivize measures that exacerbate one N impact while addressing another, a phenomenon known as pollution swapping[16]. For example, concentrated animal feeding operation (CAFO) regulations in the U.S. have led to the creation of manure lagoons to reduce NO_3^- run-off into waterways, which has inadvertently boosted NH_3 emissions[17]. The importance of a more integrated approach has been recognized in recent policy-relevant reports (see Discussion below)[2].

[Insert Figure 1 here]

Mixed agricultural policies dominate sectoral focus

From a sectoral perspective, agriculture is the dominant focus representing two-thirds of sector policies. As with sinks, this mirrors the distribution of N pollution by sector, with the remainder coming from energy, biomass burning and human and food waste[13]. However, an examination of the policy categories that make up the agriculture total reveal a mixed picture (Figure 2). Over two-thirds of the policies are either commerce (466) or pro-nitrogen (174) policies. As noted above, this is likely an underestimate given the environmental focus of the ECOLEX database. Only 190 agricultural policies (approximately 20%) are core N policies. By contrast, core N policies dominate all non-agricultural sectors, from 66% of policies in the energy sector, to 92% of policies in the transport sector. Indeed, when only core N policies are considered, the waste sector has the most N policies (201), followed closely by agriculture, together constituting almost 70% of sectoral policies.

The high proportion of core N policies in non-agricultural sectors is likely due to at least two factors: first, most non-agricultural N pollution is point-source, making policy measures easier to monitor and enforce given the more limited number and tractable nature of emission sources[18]. Moreover, market-ready and cost-effective mitigation options exist across most non-agricultural N pollution sources that do not require prohibitively costly modifications or system changes. For example, N_2O and NO_x emissions from nitric acid production can be reduced by up to 95% using iron zeolite catalysts in the tail-gas stream, and tertiary treatment of wastewater streams can lead to 80% N removal[19,20]. Second, N pollution from most non-agricultural sectors is solely a by-product loss, making it a much more straightforward environmental pollution problem. By contrast, agricultural N is an essential component of any food system, requiring a more nuanced approach that reflects its dual role as resource and pollutant : completely eliminating N consumption and loss is not an option and mitigation needs to be balanced against other key priorities such as food security[21].

[Insert Figure 2]

The skew towards commerce and pro-nitrogen policies in the agricultural sector is even more pronounced when disaggregated across regions. Figure 3 shows the breakdown of agricultural policies by policy category across OECD countries, non-OECD/high N surplus countries (e.g. China) and non-OECD/low N surplus countries (e.g. Malawi). The high/low N surplus threshold is set at 50 kg N ha^{-1}[22]. Even though OECD countries are frequent leaders in environmental policy development[23], the number of core N policies is equivalent to the number of commerce and pro-nitrogen policies (104 vs. 95). The latter policy categories dominate in non-OECD countries, making up over 75% of agricultural N policies (Figure 3). This underlines the complex relationship humanity has with N, particularly in the developing world, given its dual role as an essential input in food production and a major environmental pollutant. Agriculture is still a dominant economic force in many non-OECD countries – in sub-Saharan Africa, for example, the sector is responsible for employing two-thirds of the labor force and over 30% of GDP creation[24]. The pressure on non-OECD countries to continue to prioritize food production over environmental protection is expected to intensify over the coming decades given high projected rates of population and income growth and increasing demand for meat[22,25]. This inherent tension between N as an essential resource and pollution source is encapsulated in several of the Sustainable Development Goals (SDGs), with improved N management essential to both ending hunger (SDG 2) and protecting the environment and human health (SDGs 6, 12, 13, 14 and 15).

[Insert Figure 3]

Discussion

The dominance of water- and air-focused policies in the database mirrors the distribution of global environmental and human health costs associated with N pollution, as noted above. Notably, it also mirrors a broader shift to policies and rhetoric that prioritize national economic interests ahead (and often regardless) of the international consequences, as embodied in the leadership of heads of state such as Donald Trump and Jair Bolsanaro. This is especially important for global issues such as climate change, where the window for action to stay below dangerous temperature threshold grows increasingly small. In a world increasingly turning inward it could therefore be important to prioritize climate actions where the local benefits significantly outweigh the global benefits. The ratio of local to global benefits from reducing N pollution is significantly greater than several other major climate actions that have been studied to date. For example, the air quality benefits of decarbonizing the global energy system (\$49 per ton CO_2) are similar to the social cost of carbon (\$39 per ton CO_2)[26]. By contrast, less than 3% of the economic damage caused by N pollution is global in nature (i.e. the climate and ozone impacts from N_2O) (Figure 1b). Yet, reducing N_2O emissions could make an important contribution towards international climate targets: it is responsible for 6% of annual global greenhouse gas emissions in terms of CO_2, and ambitious mitigation could avoid emissions equal to 5–10% of the remaining carbon budget consistent with a 2 ^{o}C world[15].

Lack of policy integration

Several important lessons for N policymaking can be drawn from this database of national and regional N policies. First, there is an almost complete lack of integration across environmental sinks. While this is a common feature of environmental policy across the world, the negative consequences specifically for N pollution are particularly acute given the risk of pollution swapping as a result of the N cascade. Absent a more unified approach to N policy, policymakers are rolling the dice regarding environmental outcomes: sometimes an N policy may create co-benefits by serendipitously reducing losses of a number of N compounds not directly targeted, sometimes it may do the opposite[16].

It is perhaps naïve to expect an immediate overhaul of the existing N policy landscape towards wholly integrated policies – holistic, economy-wide strategies to reduce, recycle, store and ultimately denitrify (i.e. return to the atmosphere as N_2) excess N in all forms and from all sources. However, one interim step could be to incentivize the adoption of N mitigation measures that address total N pollution rather than one specific form – addressing the source of the issue, rather than any one of its multiple symptoms. For example, instead of a policy encouraging winter storage of manures which may stimulate NH_3 emissions while reducing NO_3^- run-off, a policy could support efforts to increase manure recycling by creating a robust market for recycled fertilizers, as done in the EU's Circular Economy package[27,28]. The choice of indicator for measuring progress is important as it can influence the types of practices and technologies adopted – N surplus or use efficiency in agriculture, for example, are more comprehensive and easily measurable metrics of potential N loss than the emissions or losses of a specific N compound[29]. A wide-ranging database of N mitigation measures is currently under development as part of the International Nitrogen Management System, a new project launched in 2017 by UNEP with funding from the Global Environment Facility (www.inms.international). This measures database could be a useful decision-support tool in helping policymakers select comprehensive N pollution mitigation measures most appropriate to their specific political, geographic and climatic context.

Another obstacle to integration is the professional incentives faced by policymakers: they are often assigned to a sink-specific team within an environmental ministry and are evaluated on the performance of sink-specific objectives over a relatively short and politically determined timeframe. In short, there is also a lack of institutional integration. These dynamics make addressing longstanding, cross-cutting issues like N pollution even more challenging. To put this in economic terms, introducing a new approach to environmental policy in an institutional environment not built for it can create high, and possibly insurmountable, transaction costs[30]. Changing this incentive system to encourage cross-pollination across teams and the development of more holistic, coherent mitigation approaches could be as important as any substantive change in N policy.

Balancing humanity's complex relationship with N

The dominance of commerce and pro-nitrogen policies in the agricultural sector is surprising given the focus of the ECOLEX database on environmental law, highlighting humanity's complex relationship with N as both an essential resource and major pollutant. One potential avenue for policy reform is to amend these policies to incentivize improved N management. For example, pro-nitrogen policies such as subsidies could integrate cross-compliance, making their receipt conditional on farmers meeting certain environmental standards. In the EU, cross-compliance is a core component of the Common Agricultural Policy, where compliance with a range of policies covering environment, food safety, animal and plant health and animal welfare is a key condition for farmers to receive direct payments to support agricultural income. This includes N-relevant policies such as the 1991 Nitrates Directive, the 1986 Sewage Sludge Directive, the 1992 Habitats Directive and the 1979 Birds Directive[31]. Similarly, commerce policies could be amended to, for example, include quality and testing standards for next generation N inputs, thereby creating a more stable business environment that may stimulate increased R&D into more environmentally friendly fertilizers and spur farmer uptake[32].

Linked to this, the small number of R&D policies in our database (less than 1% of the total) could be a reflection of the conservative approach to innovation taken by several of the central actors responsible for N pollution. For example, one recent estimate suggests that the global research and development budget for the entire fertilizer industry, including manufacturing, is US$100 million per year, equivalent to 0.1–0.2% of its revenue. By comparison, pharmaceutical and seed industries devote 10–20% of their revenues to research and development[32]. Another recent study in the U.S. shows less than 10% of farmers routinely using N best management practices or technologies, demonstrating little appetite for testing and applying new knowledge[33].

Environmental policy in the agricultural sector

The small proportion of core N policies in the agricultural sector may be a reflection of the difficulty of implementing environmental policies in this sector. Most policies to address agricultural N pollution focus on changing farmer behavior and doing so is extremely difficult because of challenges in monitoring and enforcement, as well as deeper economic and cultural factors that motivate farmer nutrient management decisions[33,34]. Even in countries where funding for adoption of N best management practices has increased dramatically over the past decade, such as the US, there has been very limited uptake in farm-level N management practices and continued increases in the loss of all major N compounds to the environment[32]. Consequently, one option is for policymakers to focus on agri-food chain actors beyond the farm capable of influencing farm-level N management, from the fertilizer industry to wastewater treatment companies. This would shift the regulatory burden away from farmers and thereby transform an intractable non-point source problem into a series of more manageable point source approaches[35]. Policy examples include imposing product or design standards on the fertilizer industry, akin to the fuel efficiency standards imposed on automobile manufacturers, to drive innovation and farmer uptake of enhanced efficiency fertilizers[32]. In short, policymakers may have to be creative in order to avoid the pitfalls of farmer-focused policies while spurring reductions in agricultural N pollution.

Next steps

Given that N pollution is still emerging as a critical environmental issue, it is notable that 2726 national and regional N policies are currently in force around the world. These policies, assembled and analyzed for the first time, reflect N pollution dynamics in some important ways – including the distribution of environmental and human health costs – but fall far short in others: particularly in terms of integration across environmental sinks and the dominance of commerce and pro-nitrogen policies, especially in agriculture. Next steps include ground-truthing the N policies in this database with bottom-up, national efforts. The INMS project and the new Interconvention Nitrogen Coordination Mechanism under UNEP will be important tools in this regard as they encourage countries to build sustainable N management roadmaps. Looking ahead, there are many questions this database could help explore, including an evaluation of the environmental and economic effectiveness of different N policy types as well as their social impacts on different actors in the agri-food chain. This study marks an important step in developing N policies that reflect the latest scientific understanding of the N cycle, which could ultimately move humanity closer to achieving its ambitious yet necessary environmental and sustainable development goals over the coming decades[13].

Figure captions

Figure 1 **Distribution of core nitrogen policies and nitrogen pollution impacts according to environmental sink**. Pie charts show a) the number of core N policies distributed by sink, and b) the estimated global annual cost of nitrogen pollution by sink in 2014 USD trillions over the period 2000-2010 (Kanter, 2018, adapted from Sutton et al. 2013).

Figure 2 **Distribution of nitrogen policies by sector and breakdown of agricultural policy types.** While agriculture dominates sectoral nitrogen policies, a closer look reveals that over two-thirds of these policies are either commerce or pro-nitrogen policies with the aim of facilitating and incentivizing nitrogen production and consumption.

Figure 3 **Agricultural N policies by category and region**. Commerce and pro-nitrogen policies are the dominant policy category, particularly in non-OECD countries, revealing nitrogen's complicated dual role as an essential input to food production and a major environmental pollutant.

Author contributions

D.R.K. conceived and led the project, analyzed and interpreted the data and led drafting of the paper. O.C., O.N and M.R. analyzed and interpreted the data and contributed to the drafting of the paper. W.W. interpreted the data and contributed to the drafting of the paper.

Data availability

A preliminary version of the nitrogen policy database developed and described in this paper can be accessed here:

https://docs.google.com/spreadsheets/d/1hOfl5Np80oC4EXrNMi7emnhx3RByRFSvOfEr9f2GJC4/edit?usp=sharing

A more user-friendly version will soon be made available via the www.inms.international website. The original database used to compile our nitrogen database is ECOLEX, which can be accessed at www.ecolex.org.

Conflict of interest statement

The authors declare no competing interests.

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Methods

The database developed and presented in this paper is derived from ECOLEX (www.ecolex.org) which is a collection of over 160,000 national, regional and international environmental laws, making it the largest online collection of environmental laws in the world. It is an aggregation of the law holdings of the Food and Agriculture Organization of the United Nations (FAO), the International Union for the Conservation of Nature (IUCN) and the United Nations Environment Programme (UNEP), funded by the Dutch government and managed by IUCN's Environmental Law Centre. Each law holding has a different focus: FAOLEX – a product of the FAO Legal Office – is a database of national legislation, policies and bilateral agreements on food, agriculture and natural resources management collected by FAO, with legal and policy documents from over 200 countries and an average of 8000 new entries per year. UNEP's InforMEA Initiative is an international environmental law database comprised of treaty texts (31 global, 55 regional) and governing body decisions. Finally, the IUCN's Environmental Law Centre developed one of the first computerized legal information systems in the 1960s (ELIS), which evolved into a large set of references to treaties, national legislation, soft law and legal literature.

ECOLEX is the best environmental law resource for the purposes of this study as it is the most comprehensive in terms of sectors, issues, policy types and countries covered. This is important given N pollution's multiple sources and impacts, which occur across a range of scales, from local to global[1]. Other environmental law databases either focus on a specific issue and scale (e.g. the Global Climate Legislation Database), sector (e.g. the Policies and Management Database: Energy Efficiency), policy type (e.g. economic policy instruments in the OECD's Database on Instruments used for Environmental Policy), policy attribute (e.g. the Environmental Policy Stringency Index) or set of countries (e.g. Inventory of Support Measures for Fossil Fuels)[2]. Despite ECOLEX's broad coverage, it is still dependent on what policies the FAO, IUCN and UNEP have been able to collect and put online. Consequently, countries with fewer publicly available and digitally recorded government legal records may be underrepresented in the database. Furthermore, given the environmental focus of ECOLEX, pro-N and commerce policies are likely underrepresented as well.

Our search of the ECOLEX database focused on its "legislation" category given our focus on national and regional policies, thereby excluding its catalogue of treaties, treaty decisions, jurisprudence and legal literature. We narrowed our focus to include only legislation that is currently in force. Consequently, legislation that has been repealed or replaced was not considered in our analysis. Each ECOLEX record includes country, year, subject, key words, policy abstract and a link to the original policy text. A first sweep of ECOLEX involved searching for several keywords linked to nitrogen (N) pollution: fertilizer, manure, nitrogen, nitrogen pollution, nutrient pollution, nitrate, nitrates, ammonia, nitrogen oxides, nitrous oxide, N_2O, NH_3, NO_3, NO_x, eutrophication, hypoxia, air quality, air pollution, emissions, groundwater quality, groundwater pollution, freshwater quality, freshwater pollution, water quality, ozone depletion, climate change, greenhouse gas, agrochemical and effluent. This returned over 15,000 results. Each result was then analyzed for relevance and categorized as an N policy or removed from the dataset using criteria described in detail below. If categorization was not possible from the policy abstract due to lack of detail, then the original text of the policy itself was analyzed for relevance. Policy abstracts and texts that were not in English or French were translated to English using Google Translate. The policies ultimately included in our database as N policies were tagged based on environmental sink (air, water, soil, climate or ecosystem), economic sector (agriculture, energy, industry, transport or waste), spatial scale (local, regional, national, or international) and policy type (regulatory, economic, data & methods, R&D, framework, commerce and pro-nitrogen). Most policies were not tagged in every category as many are either sink-focused, sector-focused or broader in nature. The database can be accessed using this link: https://docs.google.com/spreadsheets/d/1hOfl5Np80oC4EXrNMi7emnhx3RByRFSvOfEr9f2GJC4/edit?usp=sharing

As noted in the main text, given the large number of N policies we identified and the lack of detailed information directly available from the ECOLEX, this initial analysis is focused on the total number of N policies and several other defining characteristics. We do not weight policies differently based on scope, stringency, effectiveness or any other policy criteria. This means that, for example, a regulatory policy in the agricultural sector could theoretically range from a comprehensive strategy for transitioning to sustainable agriculture built on an array of targets and restrictions, to a narrower policy that institutes new air quality standards for NH_3 from poultry farms. This is a weakness of our approach and will be the focus of future work as we do more in-depth analysis of each policy, which will enable us to create more detailed sub-categories for each sink and sector and classify them according to a number of policy criteria. That being said, the act of drafting, negotiating and implementing any legal instrument requires considerable political will, demonstrating significant interest and prioritization. We consequently believe that total number of policies is an acceptable first proxy for analyzing the state of N policies around the world.

As noted below and in the main text, the only differentiation we make with regards to stringency is the creation of the "core" N policies category in order to isolate those policies that set quantifiable and enforceable constraints on N production, consumption and/or loss. The emphasis in this study is on whether the sinks and sectors covered by N policies reflect our current scientific understanding of the problem and what the balance is between pro-N policies and N mitigation policies – questions that can still be explored with this more basic unit of analysis.

Policy type categorization

We adapted the policy categories used in the International Energy Agency's Policies database and the NewClimate Institute policy database to the N context[3]. The established regulatory, economic, data & methods and R&D policy categories are modified to fit the needs of our database:

1. We define regulatory policies as ones that set quantifiable limits or restrictions on N production, consumption and loss. For example, legislation that includes emissions limits, fertilizer restrictions or water quality standards are all considered regulatory policies. This type of policy often has an enforcement mechanism (e.g. fines or penalties for non-compliance).
2. We define economic policies as ones that use financial incentives and signals to spur quantifiable improvements in N management and N mitigation. Policies can include fees, permits, taxes, subsidies and market mechanisms such as carbon and water trading.
3. Data & methods policies establish data collection and reporting protocols for various aspects of N pollution, but do not set environmental standards or enforce them. These policies can also include standards for communicating information to the public, via, for

example, sustainability reports, or to the government via environmental impact assessments and other means.

4. R&D policies are defined as those allocating funding for R&D into both the effects of N pollution on the environment and human health, and new technologies that could improve N management.

The sum of regulatory and economic policies is classified as core N policies in our database as they directly address N production, consumption or loss in a measurable way. For regulatory policies, measures like emissions targets or use restrictions give a quantitative indication *ex-ante* of what the outcome will (or at least should) be in terms of pollution reduction. By contrast, the pollution reductions resulting from economic policies like taxes and fees can only be estimated *ex post*, once the policy has been implemented. Despite this important difference, both regulatory and economic policies set quantifiable and enforceable constraints on N production, consumption and loss, and so we consider the sum of both to be core N policies in our database.

We also added three new categories to account for the unique characteristics of N dynamics and policy. The first is “framework policies”, a diverse category which includes broad, high-level environmental and agricultural policies that introduce a new national strategy or set of objectives that specifically list N production, consumption or loss as a focal point (without including specific targets). Another type of framework policy is where N policymaking authority is delegated from one governing body to another, but again with no specific targets listed. Specific examples are listed in the main text. Policies that were too broad (e.g. a Sustainable Development Goals strategy that briefly mentions the importance of sustainable agriculture, or a policy that delegates authority over an entire economic sector or region) were excluded from this category and removed from the database.

The second and third categories we created for this database were “commerce” and “pro-nitrogen” policies. Commerce policies are those that regulate an aspect of the business environment surrounding N production and consumption. Policies include fertilizer labeling, registration, classification, and trade, product quality assessments, as well as sewage sludge and manure processing. Pro-nitrogen policies are those that lower the price of N production and consumption via government aid or other means, usually incentivizing higher farmer-level N use. Both of these policy types are important to include in an N policy database (even one with an environmental focus) given the indirect influence these policies have on N pollution as a result of how they affect N production and consumption. Moreover, the sheer number of policies in these categories, despite ECOLEX being an environmental law database, highlights the complex relationship humanity has with N in its dual role as an essential resource and major pollutant.

Given the focus of this study on the environmental impacts of N pollution, we do not consider policies related to food safety (e.g. NO_3^- residue standards on food for safe human consumption), GMOs, safe drinking water (specifically where it concerns treatment standards for human consumption only) and hazardous chemicals/waste. We also only consider biodiversity policies as relevant to our purposes if they discuss agricultural buffer zones or explicitly mention fertilizer restrictions in some way. Climate and ozone policies are only included if they explicitly mention N_2O. Air pollution policies are only included if they explicitly mention NO_x or NH_3. Soil erosion and soil health policies are only included if they mention limiting nutrient run-off as an explicit goal. Aquaculture policies are only considered if they set water quality standards for open bodies of water as opposed to enclosed fisheries. Landfill and solid waste management policies are only counted if they include specific restrictions on nutrient run-off. Renewable and biofuel policies are only counted if N mitigation is a central policy goal. Policies subsidizing organic agriculture, including increased manure recycling, do count as N policies in our database, because they ultimately encourage a more circular economy in the agricultural sector, despite the risk that N may continue to be applied excessively.

Other organizational notes

Policy clusters

A recurring feature in the N database is networks of policies organized around the same goal within a country or region. For example, there may be a national-level policy that is then implemented by a suite of other policies at the state/province/municipal level and they are all included as separate entries within ECOLEX. There may be policies that set the data reporting requirements for another policy in the database or amend a particular aspect of another policy, or create institutions/ministerial units to implement another policy. These are all relevant, however we decided that counting each of them individually as N policies would be over-counting for the purposes of our database. Consequently, we create policy clusters – a collection of policies all linked by a common objective, the central node of which embodies the ultimate legislative goal that the cluster is aiming to achieve. For example, Switzerland's 1991 Federal Act on the Protection of Waters (which includes subsidies for N removal from wastewater treatment plants) has been implemented and adapted in its cantons (i.e. its regional states), with one entry for each canton in the ECOLEX database. Instead of counting each canton's policy individually, we assemble them into one policy cluster, with the original federal policy as the central node. For the purposes of accounting each policy cluster is then counted as one policy. This approach generated 254 policy clusters in our database.

European Union

The EU is a unique legislative body in that it creates laws that have the power of national law in its Member States. Consequently, each EU Directive and Regulation in the N database is counted as one policy (and marked as "EU" in terms of scale) as opposed to 28 individual national policies. The one exception to this is if the national implementation of an EU law goes above and beyond the intent of the original law by making the targets or other aspects of the law more ambitious or broader in scope. In such a case, the Member State's implementation of the EU law is counted as a separate policy in our database. If a Member State has requested a derogation from a specific EU law then this is marked in the "Notes" column for that particular law.

International agreements

N-relevant international agreements such as the Paris Climate Agreement, the Gothenburg Protocol and others are not counted in the database as our focus is on national and regional policies. Moreover, national laws simply ratifying these agreements do not count for the purposes of inclusion in our database. Similar to the EU context, national laws in this area are only counted if they go above and beyond ratification (e.g. creating specific national targets, reporting protocols etc.).

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