

1 **Gaps and opportunities in nitrogen pollution policies around the**
2 **world**

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17 This is the final author-edited version of a manuscript submitted to Nature Sustainability
18

19 The paper has been accepted for publication and is now available as
20 David R. Kanter, Olivia Chodos, Olivia Nordland, Mallory Rutigliano and Wilfried Winiwarter. Gaps and
21 opportunities in nitrogen pollution policies around the world. Nature Sustainability (2020).
22 <https://doi.org/10.1038/s41893-020-0577-7>
23

24 **Abstract**

25

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

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43 Nitrogen (N) pollution is a multifaceted and growing threat to the environment and human health.
44 Human activities have doubled the scale of the N cycle since the industrial revolution, driven by
45 increasing production and consumption of N inputs as global population and food demand per
46 capita continue to grow^{1,2}. The distinctive chemistry of the N cycle, which allows one N atom to
47 cascade through a variety of compounds once in reactive form (any form other than atmospheric
48 dinitrogen, N₂), means that N pollution exacerbates almost every major environmental issue, from
49 air and water pollution, to biodiversity loss, stratospheric ozone depletion and climate change^{3,4}.
50 Today, humanity is considered to be in the high-risk zone of the N planetary boundary – a level of
51 interference which has numerous immediate (e.g. air pollution) and long-term (e.g. climate
52 change) consequences for the Earth System^{2,5}. Moreover, its multiple forms impair humanity's
53 efforts to return or remain within a number of other planetary boundaries, including stratospheric
54 ozone depletion and climate change. Even proposed mitigation options for problems such as
55 climate change could exacerbate N pollution – for example, biofuels could be a trivial or dominant
56 source of nitrous oxide (N₂O), the third most abundantly emitted greenhouse gas, and thus offset
57 a significant proportion of the purported climate benefits of biofuel production depending on what
58 crop(s) predominate and the amount of land devoted to growing them⁶. N has thus become a major
59 international environmental policy issue in its own right, with the United Nations Environmental
60 Assembly (UNEA) calling for increased action in its Sustainable Nitrogen Management resolution
61 (UNEP/EA.4/L.16) and the 2019 Colombo Declaration outlining the ambition of a 50% reduction
62 in N waste by 2030⁷.

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64 However, there is very little sense of the current landscape of national and regional N policies
65 around the world – how many there are, what sectors they cover, what issues they address, and
66 what kinds of instruments they use. Even major N assessments over the past decade, from Europe
67 to California to India, focus largely on analyzing sources and impacts of N pollution and provide
68 limited insight into the policies in their specific regions⁸⁻¹⁰. More fundamentally, do N policies
69 match our understanding of the dominant pollution sources, the environmental sinks most
70 impacted, and the unique chemistry of the N cycle? And how do N policies reflect humanity's
71 complex relationship with N as both an essential resource and major pollutant? What is the balance
72 between policies that incentivize N use due, for example, to food security concerns, and policies
73 that prioritize N pollution mitigation? This lacuna in our understanding of N policy is particularly

74 notable given the mandate of the newly established UNEA Interconvention Nitrogen Coordination
75 Mechanism to “better facilitate communication and coherence across nitrogen policies”
76 (UNEP/EA.4/L.16) and the commitment of the Colombo Declaration signatories to “develop
77 national roadmaps for sustainable nitrogen management”. For these efforts to be successful, an
78 important first step is to establish a baseline understanding of the national and regional N policies
79 currently in force around the world.

80
81 Consequently, we created the first database of national and regional N policies with global
82 coverage. The policies are drawn from ECOLEX, the largest environmental law database in the
83 world, with records of over 160,000 national, regional and international environmental laws
84 (Methods). ECOLEX is an aggregation of the law holdings of the Food and Agriculture
85 Organization of the United Nations (FAO), the International Union for the Conservation of Nature
86 (IUCN) and the United Nations Environment Programme (UNEP). We identify and classify each
87 N policy by country, instrument type, sector, sink and scale (Methods). Consequently, our unit of
88 analysis is number of policies, which includes policy clusters: collections of policies linked by a
89 common objective in one country or region counted as one policy (Methods). This database and
90 the accompanying analysis could be a resource to policymakers developing comprehensive
91 national roadmaps for sustainable N management: helping them understand what existing policies
92 can be harnessed and what gaps need to be filled. Such roadmaps could help the international
93 community meet its numerous climate and sustainable development commitments¹³.

94 95 **Results**

96
97 We identified 2726 N policies currently in force across six continents, 186 countries, and all major
98 environmental sinks and economic sectors. Table 1 defines the policy categories (adapted from the
99 International Energy Agency’s Policies database and the NewClimate Institute’s policy database
100 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.

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103 *Nitrogen policies by policy category*

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105 While policies from each category listed in Table 1 can play an important role in N pollution,
106 certain policies are more likely to lead to measurable reductions in N pollution than others. We
107 therefore classify policies that set quantifiable and enforceable constraints on N production,
108 consumption (which includes farmer application of agricultural N inputs) and loss as “core” N
109 policies – calculated in our database as the sum of economic and regulatory policies (Table 2).
110 Constraints in this context can range from ambient pollution standards and emission limits to
111 fertilizer taxes and water trading markets. There are 1134 core N policies, constituting 42% of the
112 total. Examples of core N policies include nitrate (NO₃⁻) concentration standards in the European
113 Union’s 1991 Nitrates Directive – an ambient, water quality standard – and nitrogen oxides (NO_x)
114 emission limits on large industrial facilities in Ukraine’s 2014 National Emissions Reduction Plan
115 – a source-based, air quality standard.

116

117 936 additional policies are either framework (629), data & methods (291) or research and
118 development (R&D) policies (16). Though these policies do not directly limit N pollution, they
119 are important elements of the N policy universe. Framework policies represent the most diverse
120 policy category, referring to policies that delegate authority for N regulation from one body to
121 another and overarching environmental and agricultural policies that introduce broad objectives
122 relevant to N (Table 1). An example of the former is Canada’s 1979 Meewasin Valley Authority
123 Act, which creates the Meewasin Valley Authority in the province of Saskatchewan and gives it
124 the power to enact a range of conservation measures, including agricultural buffer zones. An
125 example of an overarching framework policy is Botswana’s 2016 National Biodiversity Strategy
126 and Action Plan, which lists the development of “regulations to limit the use of various pollutants”,
127 including fertilizers, as a required action to improve air, water and soil quality.

128

129 In contrast to policies related to N pollution mitigation, approximately 25% (656) of N policies in
130 our database are commerce and pro-nitrogen policies, focused on facilitating or incentivizing N
131 production and/or consumption. For example, Indonesia’s 2011 Regulation on Terms and
132 Procedures for the Registration of Inorganic Fertilizer is classified as a commerce policy as it
133 implements several quality standards for inorganic fertilizers, in part to “give business certainty in

134 conducting producing activities, procurement and circulation of inorganic fertilizer.” A 2009
 135 Colombian policy establishes a program to provide coffee farmers with credit to purchase fertilizer
 136 and is thus considered a pro-nitrogen policy. The total number of commerce and pro-nitrogen
 137 policies in our database is likely a conservative estimate given that ECOLEX is an environmental
 138 law database and therefore these types of policies are not a primary focus. The balance between N
 139 mitigation and consumption is discussed further below in the context of agricultural policies.

140

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

141 *Table 2 Nitrogen policy breakdown by category, environmental sink, economic sector and continent.* Categories marked with
 142 asterisks (“*”) are considered “core categories”. Categories marked with double asterisks (“**”) also include integrated N policies,
 143 which address multiple sectors and sinks of N pollution in a more unified approach. Certain policies can be classified by both sink
 144 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
 145 of sink and sector policies does not equal the total number of N policies.
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147

148 *Water dominates sink-focused policies*

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

155

156 For sinks, water is the dominant focus (almost 50% of policies), followed by air, ecosystems and
 157 climate. The focus on water holds true for core N policies and mirrors the distribution of global
 158 environmental and human health costs associated with N pollution on water and air quality,
 159 ecosystem damage and climate change, suggesting that the current N policy landscape has
 160 internalized N pollution’s most costly impacts relatively accurately (Figure 1). The major
 161 economic impacts of N-induced water pollution are increased eutrophication, declines in marine
 162 habitats and loss of recreational use, while the major air pollution impact is the increased incidence

163 of respiratory diseases¹⁴. Together, these more local impacts outweigh the global impacts of N
164 pollution from nitrous oxide's (N₂O) important role in climate change and stratospheric ozone
165 depletion by a ratio of 50:1 in terms of economic damages¹⁵ (Figure 1).

166
167 However, only 28 of the 1390 sink-focused policies address N impacts across multiple sinks – an
168 approach at odds with the cross-cutting chemistry of the N cycle, where one N atom can have a
169 variety of environmental impacts. And yet it reveals how most governments approach most
170 environmental policy, which is to legislate by sink, i.e. air vs. water vs. climate¹⁵. For example, in
171 the EU, NO₃⁻ pollution is controlled under the Nitrates Directive, while ammonia (NH₃) and NO_x
172 emissions are subject to the EU National Emission Ceilings legislation. Meanwhile, N₂O
173 reductions can generate credits from the EU Emissions Trading System (the world's largest carbon
174 market), but only from certain industrial sources (and not agriculture).

175
176 A siloed approach to N policy is problematic in that it can incentivize measures that exacerbate
177 one N impact while addressing another, a phenomenon known as pollution swapping¹⁶. For
178 example, concentrated animal feeding operation (CAFO) regulations in the U.S. have led to the
179 creation of manure lagoons to reduce NO₃⁻ run-off into waterways, which has inadvertently
180 boosted NH₃ emissions¹⁷. The importance of a more integrated approach has been recognized in
181 recent policy-relevant reports (see Discussion below)².

182
183 [Insert Figure 1 here]

184
185 *Mixed agricultural policies dominate sectoral focus*

186
187 From a sectoral perspective, agriculture is the dominant focus representing two-thirds of sector
188 policies. As with sinks, this mirrors the distribution of N pollution by sector, with the remainder
189 coming from energy, biomass burning and human and food waste¹³. However, an examination of
190 the policy categories that make up the agriculture total reveal a mixed picture (Figure 2). Over
191 two-thirds of the policies are either commerce (466) or pro-nitrogen (174) policies. As noted
192 above, this is likely an underestimate given the environmental focus of the ECOLEX database.
193 Only 190 agricultural policies (approximately 20%) are core N policies. By contrast, core N

194 policies dominate all non-agricultural sectors, from 66% of policies in the energy sector, to 92%
195 of policies in the transport sector. Indeed, when only core N policies are considered, the waste
196 sector has the most N policies (201), followed closely by agriculture, together constituting almost
197 70% of sectoral policies.

198
199 The high proportion of core N policies in non-agricultural sectors is likely due to at least two
200 factors: first, most non-agricultural N pollution is point-source, making policy measures easier to
201 monitor and enforce given the more limited number and tractable nature of emission sources¹⁸.
202 Moreover, market-ready and cost-effective mitigation options exist across most non-agricultural
203 N pollution sources that do not require prohibitively costly modifications or system changes. For
204 example, N₂O and NO_x emissions from nitric acid production can be reduced by up to 95% using
205 iron zeolite catalysts in the tail-gas stream, and tertiary treatment of wastewater streams can lead
206 to 80% N removal^{19,20}. Second, N pollution from most non-agricultural sectors is solely a by-
207 product loss, making it a much more straightforward environmental pollution problem. By
208 contrast, agricultural N is an essential component of any food system, requiring a more nuanced
209 approach that reflects its dual role as resource and pollutant : completely eliminating N
210 consumption and loss is not an option and mitigation needs to be balanced against other key
211 priorities such as food security²¹.

212
213
214 [Insert Figure 2]

215
216 The skew towards commerce and pro-nitrogen policies in the agricultural sector is even more
217 pronounced when disaggregated across regions. Figure 3 shows the breakdown of agricultural
218 policies by policy category across OECD countries, non-OECD/high N surplus countries (e.g.
219 China) and non-OECD/low N surplus countries (e.g. Malawi). The high/low N surplus threshold
220 is set at 50 kg N ha⁻¹²². Even though OECD countries are frequent leaders in environmental policy
221 development²³, the number of core N policies is equivalent to the number of commerce and pro-
222 nitrogen policies (104 vs. 95). The latter policy categories dominate in non-OECD countries,
223 making up over 75% of agricultural N policies (Figure 3). This underlines the complex relationship
224 humanity has with N, particularly in the developing world, given its dual role as an essential input
225 in food production and a major environmental pollutant. Agriculture is still a dominant economic

226 force in many non-OECD countries – in sub-Saharan Africa, for example, the sector is responsible
227 for employing two-thirds of the labor force and over 30% of GDP creation²⁴. The pressure on non-
228 OECD countries to continue to prioritize food production over environmental protection is
229 expected to intensify over the coming decades given high projected rates of population and income
230 growth and increasing demand for meat^{22,25}. This inherent tension between N as an essential
231 resource and pollution source is encapsulated in several of the Sustainable Development Goals
232 (SDGs), with improved N management essential to both ending hunger (SDG 2) and protecting
233 the environment and human health (SDGs 6, 12, 13, 14 and 15).

234

235 [Insert Figure 3]

236

237 **Discussion**

238

239 The dominance of water- and air-focused policies in the database mirrors the distribution of global
240 environmental and human health costs associated with N pollution, as noted above. Notably, it
241 also mirrors a broader shift to policies and rhetoric that prioritize national economic interests ahead
242 (and often regardless) of the international consequences, as embodied in the leadership of heads
243 of state such as Donald Trump and Jair Bolsonaro. This is especially important for global issues
244 such as climate change, where the window for action to stay below dangerous temperature
245 threshold grows increasingly small. In a world increasingly turning inward it could therefore be
246 important to prioritize climate actions where the local benefits significantly outweigh the global
247 benefits. The ratio of local to global benefits from reducing N pollution is significantly greater
248 than several other major climate actions that have been studied to date. For example, the air quality
249 benefits of decarbonizing the global energy system (\$49 per ton CO₂) are similar to the social cost
250 of carbon (\$39 per ton CO₂)²⁶. By contrast, less than 3% of the economic damage caused by N
251 pollution is global in nature (i.e. the climate and ozone impacts from N₂O) (Figure 1b). Yet,
252 reducing N₂O emissions could make an important contribution towards international climate
253 targets: it is responsible for 6% of annual global greenhouse gas emissions in terms of CO₂, and
254 ambitious mitigation could avoid emissions equal to 5–10% of the remaining carbon budget
255 consistent with a 2 °C world¹⁵.

256

257 *Lack of policy integration*

258

259 Several important lessons for N policymaking can be drawn from this database of national and
260 regional N policies. First, there is an almost complete lack of integration across environmental
261 sinks. While this is a common feature of environmental policy across the world, the negative
262 consequences specifically for N pollution are particularly acute given the risk of pollution
263 swapping as a result of the N cascade. Absent a more unified approach to N policy, policymakers
264 are rolling the dice regarding environmental outcomes: sometimes an N policy may create co-
265 benefits by serendipitously reducing losses of a number of N compounds not directly targeted,
266 sometimes it may do the opposite¹⁶.

267

268 It is perhaps naïve to expect an immediate overhaul of the existing N policy landscape towards
269 wholly integrated policies – holistic, economy-wide strategies to reduce, recycle, store and
270 ultimately denitrify (i.e. return to the atmosphere as N₂) excess N in all forms and from all sources.
271 However, one interim step could be to incentivize the adoption of N mitigation measures that
272 address total N pollution rather than one specific form – addressing the source of the issue, rather
273 than any one of its multiple symptoms. For example, instead of a policy encouraging winter storage
274 of manures which may stimulate NH₃ emissions while reducing NO₃⁻ run-off, a policy could
275 support efforts to increase manure recycling by creating a robust market for recycled fertilizers, as
276 done in the EU's Circular Economy package^{27,28}. The choice of indicator for measuring progress
277 is important as it can influence the types of practices and technologies adopted – N surplus or use
278 efficiency in agriculture, for example, are more comprehensive and easily measurable metrics of
279 potential N loss than the emissions or losses of a specific N compound²⁹. A wide-ranging database
280 of N mitigation measures is currently under development as part of the International Nitrogen
281 Management System, a new project launched in 2017 by UNEP with funding from the Global
282 Environment Facility (www.inms.international). This measures database could be a useful
283 decision-support tool in helping policymakers select comprehensive N pollution mitigation
284 measures most appropriate to their specific political, geographic and climatic context.

285

286 Another obstacle to integration is the professional incentives faced by policymakers: they are often
287 assigned to a sink-specific team within an environmental ministry and are evaluated on the

288 performance of sink-specific objectives over a relatively short and politically determined
289 timeframe. In short, there is also a lack of institutional integration. These dynamics make
290 addressing longstanding, cross-cutting issues like N pollution even more challenging. To put this
291 in economic terms, introducing a new approach to environmental policy in an institutional
292 environment not built for it can create high, and possibly insurmountable, transaction costs³⁰.
293 Changing this incentive system to encourage cross-pollination across teams and the development
294 of more holistic, coherent mitigation approaches could be as important as any substantive change
295 in N policy.

296

297 *Balancing humanity's complex relationship with N*

298

299 The dominance of commerce and pro-nitrogen policies in the agricultural sector is surprising given
300 the focus of the ECOLEX database on environmental law, highlighting humanity's complex
301 relationship with N as both an essential resource and major pollutant. One potential avenue for
302 policy reform is to amend these policies to incentivize improved N management. For example,
303 pro-nitrogen policies such as subsidies could integrate cross-compliance, making their receipt
304 conditional on farmers meeting certain environmental standards. In the EU, cross-compliance is a
305 core component of the Common Agricultural Policy, where compliance with a range of policies
306 covering environment, food safety, animal and plant health and animal welfare is a key condition
307 for farmers to receive direct payments to support agricultural income. This includes N-relevant
308 policies such as the 1991 Nitrates Directive, the 1986 Sewage Sludge Directive, the 1992 Habitats
309 Directive and the 1979 Birds Directive³¹. Similarly, commerce policies could be amended to, for
310 example, include quality and testing standards for next generation N inputs, thereby creating a
311 more stable business environment that may stimulate increased R&D into more environmentally
312 friendly fertilizers and spur farmer uptake³².

313

314 Linked to this, the small number of R&D policies in our database (less than 1% of the total) could
315 be a reflection of the conservative approach to innovation taken by several of the central actors
316 responsible for N pollution. For example, one recent estimate suggests that the global research and
317 development budget for the entire fertilizer industry, including manufacturing, is US\$100 million
318 per year, equivalent to 0.1–0.2% of its revenue. By comparison, pharmaceutical and seed industries

319 devote 10–20% of their revenues to research and development³². Another recent study in the U.S.
320 shows less than 10% of farmers routinely using N best management practices or technologies,
321 demonstrating little appetite for testing and applying new knowledge³³.

322

323 *Environmental policy in the agricultural sector*

324

325 The small proportion of core N policies in the agricultural sector may be a reflection of the
326 difficulty of implementing environmental policies in this sector. Most policies to address
327 agricultural N pollution focus on changing farmer behavior and doing so is extremely difficult
328 because of challenges in monitoring and enforcement, as well as deeper economic and cultural
329 factors that motivate farmer nutrient management decisions^{33,34}. Even in countries where funding
330 for adoption of N best management practices has increased dramatically over the past decade, such
331 as the US, there has been very limited uptake in farm-level N management practices and continued
332 increases in the loss of all major N compounds to the environment³². Consequently, one option is
333 for policymakers to focus on agri-food chain actors beyond the farm capable of influencing farm-
334 level N management, from the fertilizer industry to wastewater treatment companies. This would
335 shift the regulatory burden away from farmers and thereby transform an intractable non-point
336 source problem into a series of more manageable point source approaches³⁵. Policy examples
337 include imposing product or design standards on the fertilizer industry, akin to the fuel efficiency
338 standards imposed on automobile manufacturers, to drive innovation and farmer uptake of
339 enhanced efficiency fertilizers³². In short, policymakers may have to be creative in order to avoid
340 the pitfalls of farmer-focused policies while spurring reductions in agricultural N pollution.

341

342 *Next steps*

343

344 Given that N pollution is still emerging as a critical environmental issue, it is notable that 2726
345 national and regional N policies are currently in force around the world. These policies, assembled
346 and analyzed for the first time, reflect N pollution dynamics in some important ways – including
347 the distribution of environmental and human health costs – but fall far short in others: particularly
348 in terms of integration across environmental sinks and the dominance of commerce and pro-
349 nitrogen policies, especially in agriculture. Next steps include ground-truthing the N policies in

350 this database with bottom-up, national efforts. The INMS project and the new Interconvention
351 Nitrogen Coordination Mechanism under UNEP will be important tools in this regard as they
352 encourage countries to build sustainable N management roadmaps. Looking ahead, there are many
353 questions this database could help explore, including an evaluation of the environmental and
354 economic effectiveness of different N policy types as well as their social impacts on different
355 actors in the agri-food chain. This study marks an important step in developing N policies that
356 reflect the latest scientific understanding of the N cycle, which could ultimately move humanity
357 closer to achieving its ambitious yet necessary environmental and sustainable development goals
358 over the coming decades¹³.

359

360 **Figure captions**

361

362 *Figure 1 Distribution of core nitrogen policies and nitrogen pollution impacts according to*
363 **environmental sink**. Pie charts show a) the number of core N policies distributed by sink, and b)
364 the estimated global annual cost of nitrogen pollution by sink in 2014 USD trillions over the period
365 2000-2010 (Kanter, 2018, adapted from Sutton et al. 2013).

366

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

371

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

375

376 **Author contributions**

377

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

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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/1hOf15Np80oC4EXrNMi7emnhx3RByRFSvOfEr9f2GJC4/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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Acknowledgements

We gratefully acknowledge funding from the International Nitrogen Management System, which is itself funded by the Global Environment Facility through the United Nations Environment Programme.

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495

496 **Methods**

497

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

512

513 ECOLEX is the best environmental law resource for the purposes of this study as it is the most
514 comprehensive in terms of sectors, issues, policy types and countries covered. This is important
515 given N pollution's multiple sources and impacts, which occur across a range of scales, from local
516 to global¹. Other environmental law databases either focus on a specific issue and scale (e.g. the
517 Global Climate Legislation Database), sector (e.g. the Policies and Management Database: Energy
518 Efficiency), policy type (e.g. economic policy instruments in the OECD's Database on Instruments
519 used for Environmental Policy), policy attribute (e.g. the Environmental Policy Stringency Index)
520 or set of countries (e.g. Inventory of Support Measures for Fossil Fuels)². Despite ECOLEX's
521 broad coverage, it is still dependent on what policies the FAO, IUCN and UNEP have been able
522 to collect and put online. Consequently, countries with fewer publicly available and digitally
523 recorded government legal records may be underrepresented in the database. Furthermore, given
524 the environmental focus of ECOLEX, pro-N and commerce policies are likely underrepresented
525 as well.

526

527 Our search of the ECOLEX database focused on its “legislation” category given our focus on
528 national and regional policies, thereby excluding its catalogue of treaties, treaty decisions,
529 jurisprudence and legal literature. We narrowed our focus to include only legislation that is
530 currently in force. Consequently, legislation that has been repealed or replaced was not considered
531 in our analysis. Each ECOLEX record includes country, year, subject, key words, policy abstract
532 and a link to the original policy text. A first sweep of ECOLEX involved searching for several
533 keywords linked to nitrogen (N) pollution: fertilizer, manure, nitrogen, nitrogen pollution, nutrient
534 pollution, nitrate, nitrates, ammonia, nitrogen oxides, nitrous oxide, N₂O, NH₃, NO₃, NO_x,
535 eutrophication, hypoxia, air quality, air pollution, emissions, groundwater quality, groundwater
536 pollution, freshwater quality, freshwater pollution, water quality, ozone depletion, climate change,
537 greenhouse gas, agrochemical and effluent. This returned over 15,000 results. Each result was then
538 analyzed for relevance and categorized as an N policy or removed from the dataset using criteria
539 described in detail below. If categorization was not possible from the policy abstract due to lack
540 of detail, then the original text of the policy itself was analyzed for relevance. Policy abstracts and
541 texts that were not in English or French were translated to English using Google Translate. The
542 policies ultimately included in our database as N policies were tagged based on environmental sink
543 (air, water, soil, climate or ecosystem), economic sector (agriculture, energy, industry, transport
544 or waste), spatial scale (local, regional, national, or international) and policy type (regulatory,
545 economic, data & methods, R&D, framework, commerce and pro-nitrogen). Most policies were
546 not tagged in every category as many are either sink-focused, sector-focused or broader in nature.
547 The database can be accessed using this link:
548 [https://docs.google.com/spreadsheets/d/1hOf15Np80oC4EXrNmi7emnhx3RByRFSvOfEr9f2GJ](https://docs.google.com/spreadsheets/d/1hOf15Np80oC4EXrNmi7emnhx3RByRFSvOfEr9f2GJC4/edit?usp=sharing)
549 [C4/edit?usp=sharing](https://docs.google.com/spreadsheets/d/1hOf15Np80oC4EXrNmi7emnhx3RByRFSvOfEr9f2GJC4/edit?usp=sharing)

550
551 As noted in the main text, given the large number of N policies we identified and the lack of
552 detailed information directly available from the ECOLEX, this initial analysis is focused on the
553 total number of N policies and several other defining characteristics. We do not weight policies
554 differently based on scope, stringency, effectiveness or any other policy criteria. This means that,
555 for example, a regulatory policy in the agricultural sector could theoretically range from a
556 comprehensive strategy for transitioning to sustainable agriculture built on an array of targets and
557 restrictions, to a narrower policy that institutes new air quality standards for NH₃ from poultry

558 farms. This is a weakness of our approach and will be the focus of future work as we do more in-
559 depth analysis of each policy, which will enable us to create more detailed sub-categories for each
560 sink and sector and classify them according to a number of policy criteria. That being said, the act
561 of drafting, negotiating and implementing any legal instrument requires considerable political will,
562 demonstrating significant interest and prioritization. We consequently believe that total number of
563 policies is an acceptable first proxy for analyzing the state of N policies around the world.

564

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

571

572 **Policy type categorization**

573

574 We adapted the policy categories used in the International Energy Agency’s Policies database and
575 the NewClimate Institute policy database to the N context³. The established regulatory, economic,
576 data & methods and R&D policy categories are modified to fit the needs of our database:

577

578 1. We define regulatory policies as ones that set quantifiable limits or restrictions on N
579 production, consumption and loss. For example, legislation that includes emissions limits,
580 fertilizer restrictions or water quality standards are all considered regulatory policies. This
581 type of policy often has an enforcement mechanism (e.g. fines or penalties for non-
582 compliance).

583 2. We define economic policies as ones that use financial incentives and signals to spur
584 quantifiable improvements in N management and N mitigation. Policies can include fees,
585 permits, taxes, subsidies and market mechanisms such as carbon and water trading.

586 3. Data & methods policies establish data collection and reporting protocols for various
587 aspects of N pollution, but do not set environmental standards or enforce them. These
588 policies can also include standards for communicating information to the public, via, for

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

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

594

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

603

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

614

615 The second and third categories we created for this database were “commerce” and “pro-nitrogen”
616 policies. Commerce policies are those that regulate an aspect of the business environment
617 surrounding N production and consumption. Policies include fertilizer labeling, registration,
618 classification, and trade, product quality assessments, as well as sewage sludge and manure
619 processing. Pro-nitrogen policies are those that lower the price of N production and consumption

620 via government aid or other means, usually incentivizing higher farmer-level N use. Both of these
621 policy types are important to include in an N policy database (even one with an environmental
622 focus) given the indirect influence these policies have on N pollution as a result of how they affect
623 N production and consumption. Moreover, the sheer number of policies in these categories, despite
624 ECOLEX being an environmental law database, highlights the complex relationship humanity has
625 with N in its dual role as an essential resource and major pollutant.

626
627 Given the focus of this study on the environmental impacts of N pollution, we do not consider
628 policies related to food safety (e.g. NO_3^- residue standards on food for safe human consumption),
629 GMOs, safe drinking water (specifically where it concerns treatment standards for human
630 consumption only) and hazardous chemicals/waste. We also only consider biodiversity policies as
631 relevant to our purposes if they discuss agricultural buffer zones or explicitly mention fertilizer
632 restrictions in some way. Climate and ozone policies are only included if they explicitly mention
633 N_2O . Air pollution policies are only included if they explicitly mention NO_x or NH_3 . Soil erosion
634 and soil health policies are only included if they mention limiting nutrient run-off as an explicit
635 goal. Aquaculture policies are only considered if they set water quality standards for open bodies
636 of water as opposed to enclosed fisheries. Landfill and solid waste management policies are only
637 counted if they include specific restrictions on nutrient run-off. Renewable and biofuel policies are
638 only counted if N mitigation is a central policy goal. Policies subsidizing organic agriculture,
639 including increased manure recycling, do count as N policies in our database, because they
640 ultimately encourage a more circular economy in the agricultural sector, despite the risk that N
641 may continue to be applied excessively.

642

643 **Other organizational notes**

644

645 *Policy clusters*

646

647 A recurring feature in the N database is networks of policies organized around the same goal within
648 a country or region. For example, there may be a national-level policy that is then implemented by
649 a suite of other policies at the state/province/municipal level and they are all included as separate
650 entries within ECOLEX. There may be policies that set the data reporting requirements for another

651 policy in the database or amend a particular aspect of another policy, or create
652 institutions/ministerial units to implement another policy. These are all relevant, however we
653 decided that counting each of them individually as N policies would be over-counting for the
654 purposes of our database. Consequently, we create policy clusters – a collection of policies all
655 linked by a common objective, the central node of which embodies the ultimate legislative goal
656 that the cluster is aiming to achieve. For example, Switzerland’s 1991 Federal Act on the
657 Protection of Waters (which includes subsidies for N removal from wastewater treatment plants)
658 has been implemented and adapted in its cantons (i.e. its regional states), with one entry for each
659 canton in the ECOLEX database. Instead of counting each canton’s policy individually, we
660 assemble them into one policy cluster, with the original federal policy as the central node. For the
661 purposes of accounting each policy cluster is then counted as one policy. This approach generated
662 254 policy clusters in our database.

663

664 *European Union*

665

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

674

675 *International agreements*

676

677 N-relevant international agreements such as the Paris Climate Agreement, the Gothenburg
678 Protocol and others are not counted in the database as our focus is on national and regional policies.
679 Moreover, national laws simply ratifying these agreements do not count for the purposes of
680 inclusion in our database. Similar to the EU context, national laws in this area are only counted if

681 they go above and beyond ratification (e.g. creating specific national targets, reporting protocols
682 etc.).

683

684 **References**

685

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691