

1 **Managing a forgotten greenhouse gas under existing U.S. law:** 2 **An interdisciplinary analysis**

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38

39 **Abstract**

40

41 The United States' legal strategy for addressing climate change in recent years has relied
42 on authority from existing legislation. This has led to measures on a number of different
43 greenhouse gases, notably carbon dioxide, methane and hydrofluorocarbons. However,
44 one greenhouse gas has been largely forgotten: nitrous oxide. Nitrous oxide is the third
45 most abundantly emitted greenhouse gas in the U.S. and worldwide, as well as the largest
46 remaining threat to the stratospheric ozone layer. In addition, the nitrogen atoms in
47 nitrous oxide are part of the highly fluid nitrogen cycle where nitrogen atoms transform
48 readily among different chemical forms, each with a unique environmental and human
49 health impact – a process known as the nitrogen cascade. While the science of the
50 nitrogen cascade has been explored for over a decade, there has been little work on the
51 legal implications of this phenomenon. And yet the nitrogen cascade expands the legal
52 options available for controlling nitrous oxide. This paper studies these options in a U.S.
53 context and explores the environmental and economic impacts of enacting them. We
54 determine that the Clean Air Act, and in particular its broad authority for controlling
55 ozone depleting substances, is the most promising legal pathway for regulating nitrous
56 oxide across all major sources. Invoking such authority could generate significant climate
57 and stratospheric ozone benefits over 2015-2030, equivalent to taking 12 million cars
58 permanently off the road, and 100 million chlorofluorocarbon-laden refrigerators out of
59 service. The economic benefits could sum to over \$700 billion over 2015-2030, with
60 every \$1.00 spent on abating emissions leading to \$4.10 in societal benefits. The bulk of
61 these benefits would come from reductions in other forms of nitrogen pollution such as

62 ammonia and nitrate, highlighting the important and multiple co-benefits that could be
63 achieved by abating nitrous oxide emissions. With the Paris Climate Agreement calling
64 for limiting global temperature increases to “well below” two degrees Celsius, all
65 mitigation opportunities across all sectors need to be considered. This paper suggests that
66 nitrous oxide warrants more attention from policy-makers in the U.S. and around the
67 world.

68

69 **Key words:** Nitrous oxide; nitrogen cascade; existing legal authority; cost-benefit
70 analysis

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73 **1. Introduction**

74

75 On a sweltering day in June of 2013, President Obama outlined his administration’s
76 strategy for addressing climate change in his second term. With Congress having failed to
77 pass new climate legislation in his first term, he decided to rely solely on existing
78 executive authority to regulate greenhouse gas (GHG) emissions. This option had been
79 bolstered in 2007 by the US Supreme Court decision *Massachusetts vs. EPA* that
80 classified GHGs as air pollutants for the purposes of regulation under the Clean Air Act.
81 In 2013, the President began to exercise this authority. He directed the Environmental
82 Protection Agency (EPA) “to put an end to the limitless dumping of carbon pollution
83 from our power plants, and complete new pollution standards for both new and existing
84 power plants” (Obama, 2013).

85

86 The regulations and targets that followed put limits on carbon dioxide (CO₂) emissions
87 from coal-burning power plants, while other initiatives (such as a bilateral agreement
88 with Canada in March 2016) aim to reduce methane (CH₄) emissions from natural gas
89 installations and pipelines. At the same time, the U.S. partnered with Canada and Mexico
90 to propose an amendment to the 1987 Montreal Protocol that would phase down the
91 production and consumption of hydrofluorocarbons (HFCs). While these approaches
92 cover several of the major sources of U.S. GHG emissions, they do not cover them all.
93 And if the international community is to meet the temperature goal outlined in the Paris
94 Climate Agreement – to “hold the increase in global average temperature to well below
95 2°C and to pursue efforts to limit the temperature increase to 1.5°C” (Paris Climate

96 Agreement, Article 2.1) – then a comprehensive mitigation strategy that includes all
97 GHGs is required (Gernaat et al., 2015). One GHG that has received little attention under
98 the U.S. strategy is nitrous oxide (N₂O). Its unique chemistry gives policy-makers
99 significantly more legal options for managing its emissions. This study identifies and
100 evaluates the most promising legal options under U.S. law for directly and indirectly
101 regulating N₂O emissions using existing authority, and quantifies the environmental and
102 economic impacts of doing so.

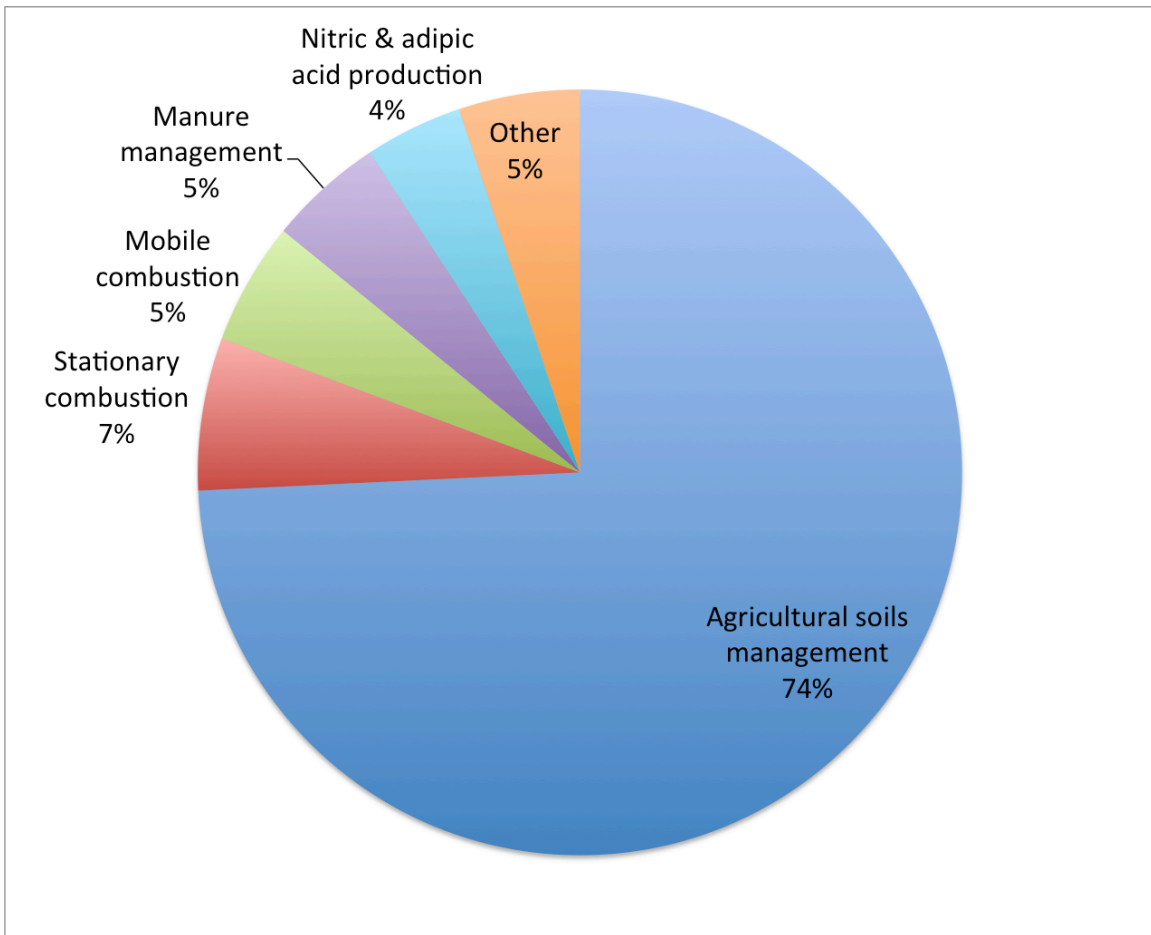
103

104 *Nitrous oxide and the nitrogen cascade*

105 In terms of CO₂ equivalents (CO₂e), N₂O is the third most abundantly emitted GHG in
106 the U.S. and worldwide (Myhre et al., 2013, USEPA, 2015a). It was responsible for 6%
107 of total U.S. CO₂e emissions in 2013 (USEPA, 2015a). It has an atmospheric lifetime of
108 116 years, and atmospheric concentrations have increased from mid-19th century levels of
109 approximately 275 parts per billion (ppb) to 328 ppb in 2015 (Butler and Montzka, 2015,
110 Prather et al., 2015). The major source in the U.S. is agricultural soils (74%). Other
111 sources include stationary combustion (7%), mobile combustion (5%), manure
112 management (5%) and nitric and adipic acid production (4%) (USEPA, 2015a – Figure
113 1). N₂O is also now the most abundantly emitted ozone depleting substance, following
114 the phase-out of more damaging compounds such as chlorofluorocarbons (CFCs;
115 Ravishankara et al., 2009). Furthermore, N₂O is a key component of the nitrogen (N)
116 cycle (Ravishankara et al., 2009, Sutton, 2013). The planetary boundary for N (a level of
117 human interference beyond which environmental damage increases dramatically, and
118 perhaps permanently) is one of two that humanity is significantly exceeding (Steffen et

119 al., 2015). And the unique chemistry of the N cycle means that once an N atom is in
120 “reactive” form (any form other than atmospheric dinitrogen, N_2) it can convert readily
121 among multiple chemical forms, each with a specific impact on the environment and
122 human health, thereby increasing the risk of exceeding other planetary boundaries. For
123 example, an N atom may first be applied to a field as N fertilizer, before being first
124 volatilized as ammonia (NH_3) and negatively impacting air quality; it may then be
125 deposited, oxidized and subsequently leached into a waterway as nitrate (NO_3^-),
126 contributing to eutrophication and polluting aquatic ecosystems (along with phosphorus
127 run-off); the same N atom can be denitrified to N_2O , exacerbating climate change and
128 stratospheric ozone depletion (Birch et al., 2010). This phenomenon is commonly
129 referred to as the N cascade (Galloway et al., 2003).

130



131

132 **Figure 1** Anthropogenic N₂O emission sources in the U.S. in 2013. The dominant source
 133 is agricultural soils management, which includes emissions from mineralization,
 134 asymbiotic fixation, fertilizer and manure use, crop residues and sewage sludge (adapted
 135 from USEPA, 2015a).

136

137 While the N cascade is the subject of a large and growing scientific literature, it has yet to
 138 receive the same level of attention from legal scholars, despite being ripe for analysis.

139 The multitude of impacts that one atom of N can create gives environmental policy-
 140 makers several legal options to how to manage it: existing environmental law related to
 141 air and water pollution, biodiversity preservation, climate change and stratospheric ozone
 142 depletion could all be justifications for addressing various sections of the N cascade. And
 143 because of the tightly coupled nature of the N cycle, efforts to reduce one particular

144 component of the N cascade could impact N₂O emissions as well. Conversely, efforts to
145 reduce N₂O emissions could deliver a suite of benefits throughout the entire N cascade
146 (Horowitz et al., 2016). For example, the European Union’s Nitrates Directive focuses on
147 reducing NO₃⁻ leaching and runoff from farms. A recent study estimated that this
148 Directive not only reduced N leaching and runoff by 16% during 2000-2008, but also
149 reduced NH₃ by 3%, N₂O by 6% and NO_x by 9% due to lower N inputs from fertilizer
150 and manure (Velthof et al., 2014). Similar co-benefits could be achieved by
151 implementing policies focused on reducing N₂O emissions, a potential outcome this
152 paper investigates. Nevertheless, there is also a risk of pollution swapping – where
153 measures to reduce one form of N pollution exacerbate another – which we address in
154 Section 5.3. Another aspect of N pollution that sets it apart from many other
155 environmental issues and makes it a particularly challenging one to manage is that N is
156 an essential resource. The dramatic increase in global population over the past century
157 would have been impossible without the concomitant increase in our ability to intensify
158 agricultural production, which was fueled by synthetic N fertilizer (Erisman et al., 2008).
159 Feeding ten billion people by 2050 will be impossible without anthropogenic N inputs.
160 Consequently, efforts to reduce N₂O and N pollution more broadly have chiefly focused
161 on improving the efficiency with which N is used, rather than placing absolute limits on
162 its use.

163

164 The first section of this paper presents the legal analysis for identifying the most
165 promising legal pathways for limiting N₂O in the U.S. It then introduces the methods

166 used for estimating the environmental and economic impacts of pursuing these pathways,
167 before presenting the results and discussion.

168

169 **2. Legal analysis**

170

171 The focus of the legal analysis was to identify the most effective regulatory pathways for
172 reducing N₂O emissions in the US. We began by conducting a preliminary evaluation of
173 existing laws to determine whether they provided a suitable framework for controlling
174 N₂O emissions. We considered three factors:

175

176 (1) **Scope of regulatory impact**, e.g., whether the statute was a federal law that could
177 control N₂O emissions on a nation-wide scale, and whether it could be used to
178 regulate all major sources of N₂O emissions.

179 (2) **Nature of legal authority**, e.g., whether the statute included a mandate that could
180 be interpreted as requiring an agency to regulate N₂O emissions, as opposed to
181 giving an agency discretionary authority to regulate those emissions.

182 (3) **Suitability of the legal framework**, e.g., whether the statute was specifically
183 designed to address a particular N₂O-related impact or another aspect of N
184 pollution; and whether its original purpose was to regulate the types of activities
185 that are major sources of N₂O emissions.

186

187 Using this framework, we evaluated opportunities to reduce N₂O emissions under three
188 federal laws—the Clean Air Act, the Clean Water Act, and the Farm Bill—as well as
189 state programs aimed at reducing GHG emissions and N pollution.

190

191 We concluded that the Clean Air Act (CAA) provides the most suitable legal framework
192 for controlling N₂O emissions on a nation-wide scale for several reasons: it is a federal
193 law affecting the entire nation, it contains clear mandates for U.S. Environmental
194 Protection Agency (USEPA) to address both ozone depleting substances and other forms
195 of air pollution (including GHG emissions), and it includes a variety of provisions that
196 can be used to address each of the major sources of N₂O emissions. For more discussion
197 of the various legal options see (Wentz and Kanter, Forthcoming) and (Burger et al.,
198 2016). By contrast, the Clean Water Act and the Farm Bill do not include mandates to
199 federal agencies that would require or even authorize the regulation of N₂O emissions
200 from major sources. Similarly, we concluded that existing state programs do not establish
201 clear mandates or authorizations to regulate N₂O emissions, nor could they be used to
202 achieve nation-wide emissions reductions.

203

204 The Clean Air Act provides a comprehensive framework for regulating air pollution in
205 the United States, as well as GHG emissions and emissions that deplete the stratospheric
206 ozone layer. As such, it is the most promising federal statute for addressing N₂O
207 emissions. The USEPA, the agency tasked with implementing the Clean Air Act, has
208 already begun to regulate GHG emissions under this statute. Specifically, the USEPA
209 has promulgated final rules to control CO₂ emissions from new and existing power

210 plants, and GHG emissions from motor vehicles. The USEPA also recently proposed a
211 rule to reduce CH₄ emissions from new and modified sources in the oil and gas industry.
212 However, the USEPA has not yet promulgated any proposed or final rules to specifically
213 regulate N₂O emissions from any sources other than motor vehicles. Moreover, the N₂O
214 emission standards for motor vehicles are significantly higher than current average
215 emission rates, thereby acting as a cap on future emissions rather than a limit for reducing
216 current emissions (USEPA, 2014).

217

218 The USEPA could use a variety of different Clean Air Act provisions to regulate
219 domestic sources of N₂O emissions. The best fit for addressing all major sources,
220 including agricultural emissions, would be to use Title VI (“Protection of the
221 Stratospheric Ozone”). Section 615 in particular authorizes the USEPA to implement
222 regulations to control any substance, practice, process, or activity that contributes to
223 stratospheric ozone depletion. USEPA could also apply emission standards under Section
224 111 to regulate N₂O emissions from stationary sources, and Section 202 to regulate N₂O
225 emissions from mobile sources. Finally, USEPA could determine that N₂O emissions
226 contribute to international air pollution under Section 115 and use its authority under that
227 section to compel state regulation of N₂O emission sources. Table 1 compares the
228 different provisions under the Clean Air Act that could be used to address N₂O.

229

230

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232

Provision	Relevant sector	Legal Authority / Mandate
Section 615	All	USEPA shall promulgate regulations respecting the control of any substance, practice, process, or activity that may reasonably be anticipated to affect the stratosphere, especially ozone in the stratosphere, and such effect may reasonably be anticipated to endanger public health or welfare.
Section 111	Stationary sources	USEPA shall promulgate standards of performance for stationary sources to control emissions of air pollution that may reasonably be anticipated to endanger public health or welfare.
Section 202	Mobile sources	USEPA shall promulgate standards of performance for mobile sources to control emissions of air pollution that may reasonably be anticipated to endanger public health or welfare.
Section 115	All	USEPA shall issue a notice requiring states to develop emission controls as necessary to prevent or eliminate the endangerment caused to the foreign country by air emissions.

233 **Table 1** - Clean Air Act Provisions that could be used to regulate N₂O emissions. N₂O
234 was among a suite of greenhouse gases defined as air pollutants for the purposes of
235 regulation under the Clean Air Act in the 2007 Supreme Court decision *Massachusetts vs.*
236 *EPA*.

237

238 **3. Environmental analysis**

239

240 The environmental analysis focuses on N₂O emissions sources in the U.S. where
241 abatement technologies are commercially available and there is significant emissions
242 reduction potential: agriculture (specifically, the use of fertilizer and manure), nitric acid
243 production, and gasoline-powered road vehicles. Together these sources constitute 45%
244 of anthropogenic N₂O emissions in the U.S. (USEPA, 2015a). This is lower than the 74%

245 attributed to agricultural soil management, given the limited focus on fertilizer and
246 manure use (see Section 3.1). Several of the legal options identified in Section 2 give
247 broad authority to the relevant federal agency in setting targets. In reality, target setting is
248 as much a political process as it is a scientific one (emerging from stakeholder and
249 interagency negotiations), making it difficult to assess what the targets might be. As a
250 result, for this paper we consider emissions targets based on best available technologies
251 and previously published mitigation scenarios to illustrate the potential environmental
252 and economic impacts of pursuing N₂O regulations in the U.S. We describe the targets in
253 detail below. For each source, we select or construct a business-as-usual emissions
254 scenario (where little additional effort is made to reduce N₂O) and a mitigation scenario
255 (where a concerted effort is made to reduce N₂O). For the business-as-usual scenarios, we
256 use N₂O emission projections from the EPA report “Global Mitigation of Non-CO₂
257 Greenhouse Gases: 2010-2030” (USEPA, 2013a).

258

259 *3.1 Agricultural emissions*

260 Agricultural soil management is the single largest source of N₂O emissions in the US,
261 responsible for 74% of N₂O emissions, and 4% of total US GHG emissions in 2013
262 (USEPA, 2015a). Disaggregating agricultural N₂O emissions, the USEPA attributes 54%
263 to mineralization and asymbiotic fixation, 26% to synthetic fertilizer, 16% to manure, 3%
264 to crop residues, and less than 1% to sewage sludge. USEPA uses the DayCENT model
265 (Parton et al., 2001) to derive the contribution of each source for its annual GHG
266 emissions inventory, including mineralization and asymbiotic fixation. Mineralization is
267 the biogeochemical process that converts organic N (typically decomposing organic

268 matter from earlier agricultural activities) into mineral N, making N suitable for plant
269 uptake. Asymbiotic fixation is the conversion of atmospheric nitrogen (N_2) into plant-
270 usable N by soil bacteria not directly associated with plants. While these processes are
271 affected by agricultural activities, additional research is still required to quantify how
272 different mitigation strategies affect these fluxes. It should also be noted that most
273 countries do not use biogeochemical models like DayCENT to estimate national
274 emissions, and thus attribute emissions from mineralization and asymbiotic fixation
275 emissions to other sources (like synthetic fertilizer and manure) in their GHG emissions
276 inventories. Consequently, the focus in academic, NGO and government circles (as well
277 as this paper) is on reducing agricultural N_2O (and N pollution more broadly) from
278 synthetic fertilizer and manure.

279 Synthetic fertilizer and manure have greatly increased N concentrations in agricultural
280 soils over the past century, bolstering the major biogeochemical processes that produce
281 N_2O : nitrification (the conversion of ammonium (NH_4^+) to NO_3^-), and denitrification (the
282 conversion of NO_3^- to N_2). N_2O can also be emitted indirectly once N has been lost from
283 agricultural soils in other forms, with portions of NH_3 , NO_x and NO_3^- losses susceptible
284 to N_2O conversion. N_2O emissions from manure management are accounted for
285 separately from emissions linked to the field application of manure, with the former
286 constituting an additional 5% of US N_2O emissions. This source includes emissions from
287 the treatment, storage, and transportation of livestock manure. While the mitigation
288 strategies outlined below do not directly address N_2O emissions from manure
289 management, measures to reduce N excretion rates per animal are part of the mitigation

290 scenario, which would reduce the overall amount of manure N that would require
291 management.

292

293 For the business-as-usual emissions scenario, we use the EPA N fertilizer and manure
294 forecasts (USEPA, 2013b), which project an 8% increase in N fertilizer consumption and
295 an 18% increase in manure production between 2010 and 2030 (Table 2). For our
296 mitigation scenario, we use the Case 3 scenario from the UNEP 2013 report “Drawing
297 Down N₂O to Protect Climate and the Ozone Layer”, which assumes that an increase in
298 fertilizer use efficiency reduces fertilizer demand by 15% and the N₂O emission factor
299 for fertilizer by 20% relative to business-as-usual. It also assumes that improvements in
300 manure management reduce N excretion per unit animal product by 30% and the N₂O
301 emission factor for manure production by 10% relative to business-as-usual (Table 2).
302 Implementing such a scenario would require significant uptake in the use of fertilizer best
303 management practices, such as precision and split application (the former uses GPS
304 technology and soil testing to identify the N requirements of a particular field more
305 precisely; the latter refers to the application of several smaller fertilizer doses throughout
306 the growing season that coincide with the times that crops most need N). It would also
307 require the use of enhanced efficiency fertilizers – fertilizer technologies such as N
308 inhibitors and slow- and controlled-release fertilizers that delay the release of N in the
309 soil to better coincide with plant nitrogen demand – thereby reducing excess N in the soil
310 and the potential for N₂O emissions (Akiyama et al., 2010, Abalos et al., 2014). For N₂O
311 emissions from manure, measures to reduce N excretion per unit animal involve a
312 combination of targeted improvements in animal breeding, feed quality and management,

313 and herd management. Reducing the N₂O emission factor for manure consists largely of
 314 applying N inhibitors to grazing land and avoiding animal N deposition on wet soils
 315 (UNEP, 2013).

316

	2015	2020	2025	2030
<i>BAU scenario</i>				
N ₂ O EF fertilizer (%)	1.5	1.5	1.5	1.5
N ₂ O EF manure (%)	1.7	1.7	1.7	1.7
Fertilizer (Mt N)	11.5	11.8	12	12.2
Manure (Mt N)	8.5	9.1	9.5	10.0
<i>MIT scenario</i>				
N ₂ O EF fertilizer (%)	1.5	1.4	1.3	1.2
N ₂ O EF manure (%)	1.7	1.6	1.6	1.5
Fertilizer (Mt N)	11.5	11.2	10.8	10.4
Manure (Mt N)	8.5	8.1	7.6	7.0

317 **Table 2** Projections of N₂O emission factors used or derived from EPA (2013a) and Ogle
 318 et al. (2014), and projected U.S. fertilizer consumption and manure production out to
 319 2030, under a business-as-usual (BAU) emissions scenario – representing little additional
 320 effort to reduce N₂O – and a mitigation (MIT) scenario, where a concerted effort is made
 321 to reduce N₂O. The mitigation scenario is based on the Case 3 scenario in UNEP (2013).
 322 The emission factors include both direct N₂O emissions from field application of
 323 fertilizer and manure as well as indirect emissions from N volatilization and leaching.
 324 They do not include emissions from human waste management or livestock manure
 325 management.

326

327 As mentioned in the introduction, the unique chemistry of the N cycle means that efforts
 328 to reduce N₂O emissions by increasing N use efficiency could also potentially reduce
 329 other forms of agricultural N losses (Kanter et al., 2013). To estimate these impacts, we
 330 use emission factors from Ogle et al. (2014), which are largely based on IPCC default
 331 values (Eggleston, 2006, Ogle, 2014). For NH₃ and NO_x, Ogle et al. (2014) estimates that
 332 10% of synthetic fertilizer N and 20% of manure N is volatilized as NH₃ and NO_x (with
 333 NH₃ dominating). Of this, 1% is subsequently transformed into N₂O. For N leaching, the
 334 Ogle et al. (2014) emission factor is 30% in agricultural systems without cover crops,

335 18% in systems with leguminous cover crops, and 9% in systems with non-leguminous
336 cover crops (however, currently only 1% of US cropland systems use cover crops –
337 (Wallander, 2013)) Of this, 0.75% is subsequently transformed into N₂O.

338

339 *3.2 Non-agricultural emissions*

340 Non-agricultural sources are responsible for 20% of anthropogenic N₂O emissions in the
341 US (USEPA, 2015a). They include industrial processes, stationary combustion, as well as
342 transportation and waste management. For the purposes of this analysis we focus on
343 specific sub-sectors within each of these sources where technologies already exist that
344 have been demonstrated to significantly reduce N₂O emissions.

345

346 For industrial processes we focus on nitric acid production, responsible for 75% of
347 emissions from this sector. All three facilities producing the other major source of
348 industrial N₂O in the US – adipic acid production – already have N₂O abatement
349 technology installed (USEPA, 2015a). While newer technologies exist that can reduce
350 N₂O emissions from adipic acid production even further, their emission reduction
351 potential in the U.S. would be relatively small compared to mitigation opportunities in
352 other sectors (but may still be cost-effective). For mobile combustion we focus on
353 gasoline-fueled road vehicles, responsible for 76% of N₂O emissions from this sector in
354 2012 (USEPA, 2015a). Other sources include diesel-fueled road and off-road vehicles,
355 aircraft, ships and agricultural equipment, which we judged to be either too minor or
356 having no cost-effective abatement technologies. Stationary combustion (primarily coal
357 combustion) is another key source of non-agricultural N₂O emissions. However, there are

358 fewer opportunities to reduce N₂O emissions from this sector, because most of the coal-
359 fired power plants in the US are pulverized coal plants boilers, which emit less N₂O than
360 facilities with more modern technologies (such as fluidized bed combustion) even when
361 those facilities install N₂O abatement technologies (USEPA, 2015a). Thus, we do not
362 consider N₂O emissions from stationary combustion in our analysis, but there may be
363 cost effective opportunities there. Together, emissions from nitric acid production and
364 gasoline-fueled road vehicles constitute approximately 35% of the N₂O emissions from
365 non-agricultural sources, and thus about 7% of total anthropogenic N₂O emissions in the
366 U.S.

367

368 The business-as-usual scenario from EPA (2013a) projects a 10% decrease in US N₂O
369 emissions from mobile combustion between 2010 and 2030, and a 28% increase in
370 emissions from nitric and adipic acid production. By applying the EPA's forecast
371 methodology, we can disaggregate EPA projections of N₂O emissions from nitric acid
372 production and gasoline-fueled road vehicles (USEPA, 2013b). The mitigation scenario
373 for nitric acid production assumes that by 2030 100% of US nitric acid production will be
374 produced in facilities with N₂O abatement technology, up from 28% today (USEPA,
375 2015a). This implies that by 2030 average N₂O emissions from nitric acid production
376 decrease from 7kg to approximately 0.1 kg N₂O per ton of nitric acid produced.
377 Abatement technologies currently available include catalytic decomposition and non-
378 selective catalytic reduction techniques that can reduce emissions by as much as 99%
379 (USEPA, 2013a). The mitigation scenario for mobile combustion involves applying EPA
380 Tier 2 exhaust emission factors as sector-wide targets for 2030, which would mean

381 tightening the N₂O emission caps from 0.01 g N₂O/mile to 0.0036 g N₂O/mile for
382 gasoline passenger cars and 0.0066 g N₂O/mile for gasoline light-duty trucks. For heavy-
383 duty trucks it would mean reducing the emissions cap from 0.05 g N₂O/mile to 0.0134 g
384 N₂O/mile. This would require the accelerated diffusion of a range of market-ready
385 advanced three-way catalysts that have significantly lower N₂O emission rates per mile
386 than the average of the current U.S. vehicle fleet – as assumed in UNEP (2013), but
387 which appears to be missing from the USEPA projections (USEPA, 2013b).

388

389 **4. Economic analysis**

390

391 Though the CAA does not allow for cost consideration in the setting of National Ambient
392 Air Quality Standards following *Whiman vs. American Trucking Associations*, cost
393 considerations are required or allowed for most other performance standards and
394 regulatory programs under the CAA. Furthermore, cost-benefit analysis can make a
395 compelling case for action to policy-makers and the general public. There are two
396 elements to estimating the economic impacts of following the mitigation emissions
397 scenario vs. the business-as-usual scenario. The first is damage costs associated with each
398 form of N pollution. The second is abatement costs associated with the practices and
399 technologies required to implement N₂O reductions. For the damage costs associated with
400 N pollution, we adapt the approach followed in Kanter et al. (2015). We use a range of
401 damage cost estimates, either based on attempts to monetize the economic impacts
402 caused by the release of a kg of a particular N compound to the environment (Birch et al.,
403 2010, Compton et al., 2011, Horowitz et al., 2016) or on the amount of money society is

404 willing to pay to avoid these impacts (Gu et al., 2012, Van Grinsven et al., 2013). We
405 then average these estimates to have one damage cost per N compound. Finally, the
406 damage cost estimates used in this study are adjusted to US gross national income (GNI)
407 per capita in order to better reflect national economic conditions (Table 3). For abatement
408 costs, we use a range of sources (Kanter et al., 2015, Laboski, 2006, Roberts, 2014,
409 Sutton, 2013, USEPA, 2013a). The simplest abatement cost estimate is from Sutton et al.
410 (2013), which assumes an average abatement cost of \$0.5 (\$0.2-\$1.5) per kg N saved (in
411 2014 USD), based on cost estimates for NH₃ abatement (UNECE, 2012). This approach
412 does not differentiate between different types of best management practice and
413 technology.

414

415 More rigorous approaches to estimating abatement costs include Kanter et al. (2015),
416 which uses the IIASA GAINS model (Winiwarter, 2005) to estimate the cost of using
417 fertilizer best management practices (a blend of precision and split application), and
418 expert elicitation to estimate the price premium of enhanced efficiency fertilizers (i.e. the
419 additional costs above traditional fertilizer costs). For the former, this translates to \$0.66
420 (\$0.49-\$0.84) per kg N reduced (in 2014 USD). For the latter, the current price premium
421 for N inhibitors (defined as a percentage of the price of traditional N fertilizer) is
422 estimated at 16%, and is projected to be 11% (7%-17%) by 2035. The current price
423 premium for slow- and controlled-release fertilizers is estimated at 29%, and is projected
424 to be 21% (15%-33%) by 2035. A weighted average gives a price premium of 15%
425 (11%-24%) by 2035.

426

427 To estimate the N₂O abatement costs from manure, we use figures from EPA (2013a),
428 Laboski et al. (2006), and Roberts et al. (2014), which calculate the cost of using N
429 inhibitors once animal N has already been deposited on cropland and/or pasture. They
430 assume the cost of a generic N inhibitor is \$60-\$70 (2014 USD) per gallon, and that 1.25-
431 1.5 gallons of N inhibitor is used per ton of N applied. To compare, we also use the EPA
432 (2013a) estimate that using N inhibitors costs \$20 per hectare. And finally, to estimate the
433 costs of improving animal breeding, feed quality and management, we use the EPA
434 (2013a) estimate of \$2-\$295 per head of beef and dairy cattle, which is subsequently
435 adjusted to other forms of livestock by weight (Table 3).

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Damage costs (\$ per kg N)					
N compound	<i>Birch et al. 2010</i>	<i>Compton et al. 2010</i>	<i>Gu et al. 2012</i>	<i>Van Grinsven et al. 2013</i>	Average
N ₂ O	-	\$3.7 (2.8-4.6)	\$3.1*	\$29 (12-48)	\$12
NO _x	\$24*	\$24*	\$26 (19-34)	\$42 (7-93)	\$29
NH ₃	\$18*	\$5.2 (1.3-9.1)	\$16 (3.1-30)	\$29 (0-60)	\$17
NO ₃ ⁻	-	\$67 (66-69)	-	\$31 (12-57)	\$49

Abatement costs				
Practice	<i>Sutton et al. 2013</i>	<i>Kanter et al. 2015</i>	<i>Laboski et al. 2006;</i> <i>Roberts et al. 2014</i>	<i>EPA 2013</i>
BMPs-fertilizer (\$ ha ⁻¹)	\$11.25 (4.5-33.8)	\$14.85 (11-18.9)	-	
BMPs-manure (\$ ha ⁻¹)	""	-	-	
EEFs-fertilizer (\$ ha ⁻¹)	""	\$9 (6.6-14.4)	\$13.4 (11.3-15.8)	\$20*
EEFs-manure (\$ ha ⁻¹)	""	-	\$13.4 (11.3-15.8)	\$20*
Livestock management (\$ head ⁻¹)	""	-	-	\$150 (2-295)

450 **Table 3** Damage costs (in \$ per kg N) from four peer-reviewed studies for the four main
451 N compounds, and their averages. Abatement costs (in a variety of units) for five
452 different abatement strategies using cost estimates from five peer-reviewed studies.
453 BMPs-fertilizer and BMPs-manure refers to best management practices applied to
454 fertilizer and manure, respectively. EEFs-fertilizer and EEFs-manure refer to enhanced
455 efficiency fertilizers used in fertilizer and manure, respectively. Numbers in brackets are
456 uncertainty bounds. All values are in 2014 USD.

457 * Uncertainty ranges not reported.

458

459 In terms of non-agricultural N₂O emissions, for nitric acid production we use cost
460 estimates used by USEPA (2013a), with capital costs ranging from \$3.5-\$6.3 per ton of
461 nitric acid produced and annual operating and maintenance costs ranging from \$0.6-\$1.3
462 per ton of nitric acid produced, depending on the abatement technology. No specific cost
463 estimates were found for gasoline-fueled road vehicles, so we use the average abatement
464 cost estimate for N pollution from Sutton et al. (2013) of \$0.5 per kg N saved.

465

466 **5. Results & Discussion**

467

468 *5.1 Environmental impacts*

469 The emissions avoided by following the mitigation emissions scenario vs. the business-
470 as-usual scenario across all the sectors considered are 0.16 Mt N₂O-N yr⁻¹ by 2030 (Table
471 4, Figure 2). Much of the reduction in N₂O emissions comes from the agricultural sector,
472 given the magnitude of this source (Table 5). The avoided emissions translate to climate
473 benefits of 74 Mt CO₂e yr⁻¹ (equivalent to approximately half the current methane
474 emissions from U.S. natural gas production – EPA, 2015a) and stratospheric ozone
475 benefits of 5 kt ODP yr⁻¹ by 2030. The climate benefits by 2020 (24 Mt CO₂e yr⁻¹) are
476 equivalent to 3% of the remaining reductions needed to reach the 2020 target of cutting
477 GHG emissions by 17% below 2005 levels, and 3% of the remaining reductions needed
478 to reach the 26%-28% reductions required by 2025. Summing the benefits over the period
479 2015-2030 yields savings of 1.26 Mt N₂O-N, equivalent to 449 Mt CO₂e and 30 ODP kt.
480 The climate benefits are equal to taking 12 million cars permanently off the road. The
481 ozone benefits are equal to taking 100 million CFC-laden refrigerators out of service.

482

483 For other N compounds, following the mitigation scenario reduces NO_x and NH₃ losses
 484 by 0.4 Mt N yr⁻¹ each, and NO₃⁻ losses by 1.4 Mt NO₃-N yr⁻¹ by 2030. Summing the
 485 benefits over the period 2015-2030 yields savings of 3 Mt N for both NO_x and NH₃, and
 486 11.1 Mt NO₃-N for NO₃⁻ (Table 4). Figure 2 compares the total N₂O reductions under the
 487 mitigation scenario and business as usual.

	2015	2020	2025	2030	Sum (2015-2030)
N ₂ O (Mt N yr ⁻¹)	0	0.05	0.11	0.16	1.26
<i>Climate (Mt CO₂e yr⁻¹)</i>	0	24	49	74	449
<i>Ozone (kt ODP yr⁻¹)</i>	0	1.6	3.3	5	30
Other N compounds (Mt N yr⁻¹)					
NO _x	0	0.12	0.25	0.4	3
NH ₃	0	0.12	0.25	0.4	3
NO ₃ ⁻	0	0.45	0.93	1.4	11.1

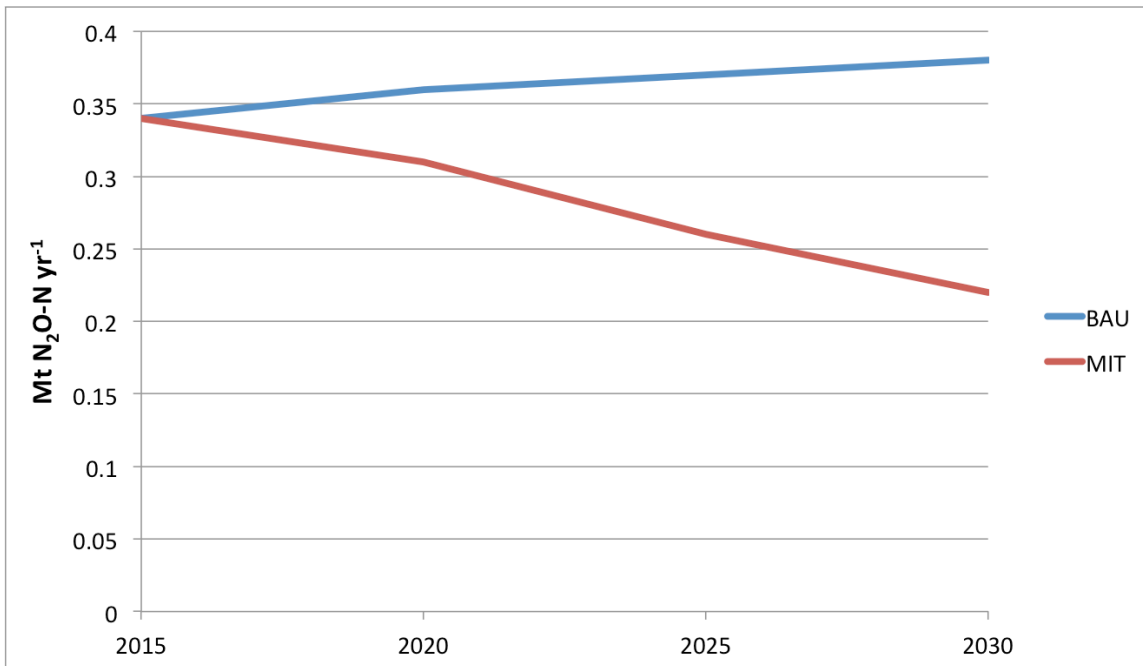
488 **Table 4** Difference in environmental impacts of following the mitigation vs. business-as-
 489 usual emissions scenario across all the sources considered. Numbers represent the annual
 490 differences in N fluxes between the scenarios in 2015, 2020, 2025 and 2030, as well as
 491 the sum of the differences over the period 2015-2030.

492

Source (Mt N ₂ O-N yr ⁻¹)	Scenario	2015	2020	2025	2030
N fertilizer and manure	BAU	0.28	0.29	0.30	0.31
	MIT	0.28	0.26	0.23	0.21
Gasoline-powered road vehicles	BAU	0.026	0.026	0.024	0.023
	MIT	0.026	0.021	0.017	0.012
Nitric acid production	BAU	0.036	0.039	0.041	0.044
	MIT	0.036	0.026	0.014	0.003
<i>Total</i>	<i>BAU</i>	<i>0.34</i>	<i>0.36</i>	<i>0.37</i>	<i>0.38</i>
	<i>MIT</i>	<i>0.34</i>	<i>0.31</i>	<i>0.26</i>	<i>0.22</i>

493 **Table 5** N₂O emission trajectories for both business-as-usual and mitigation scenarios
 494 from 2015 to 2030 across the sources considered in this paper: N fertilizer and manure,
 495 gasoline-powered road vehicles, and nitric acid production. The bottom row represents
 496 the sum of all three sources from both scenarios.

497



498
 499 **Figure 2** – U.S. N₂O emission trends from the sources considered in this study (nitrogen
 500 fertilizer and manure use, gasoline-powered road vehicles, and nitric acid production)
 501 over 2015-2030 in a business-as-usual versus a mitigation scenario.

502
 503 *5.2 Economic impacts*

504 The avoided economic damages from following the mitigation scenario reach over \$90
 505 billion annually by 2030, with over 99% coming from the agricultural sector (Table 6).
 506 Avoided damages due to N₂O emissions reductions constitute only 2% of this overall
 507 amount, with the bulk of the benefits coming from reductions in other N compounds –
 508 NO₃⁻ in particular, given both the higher absolute reductions and damage costs per
 509 kilogram. This demonstrates the importance of considering the N₂O mitigation co-
 510 benefits when evaluating policy options. The avoided damages in 2020 (~\$30 billion) and
 511 2025 (~\$60 billion) are within the range of estimates for avoided damages from climate
 512 change if the current US climate targets are implemented (\$16-\$150 billion in 2020 and
 513 \$24-\$247 billion in 2025, depending on the social cost of carbon used) (USEPA, 2015b).

514 Summing over the period 2015-2030, the avoided economic damages amount to over
515 \$700 billion.

516

517 The abatement costs of following the mitigation scenario reach approximately \$22 billion
518 in 2030, again with over 99% of these costs from the agricultural sector. Summing over
519 the period 2015-2030, the abatement costs amount to just over \$170 billion.

520 Consequently overall, for every \$1.00 spent on abating N₂O emissions, society is
521 projected to gain \$4.10.

522

Avoided damages (\$ billions)	2015	2020	2025	2030	Sum (2015-2030)
<i>N fertilizer and manure</i>					
N ₂ O	0	0.4 (0.3-0.9)	0.8 (0.5-1.8)	1.2 (0.8-2.7)	9.8 (6.1-21.7)
NO _x	0	3.7 (1.6-7.7)	7.7 (3.3-16)	12 (5.1-24.9)	93 (39.5-192)
NH ₃	0	2 (0.2-5.4)	4.2 (0.4-11.2)	6.5 (0.6-17.5)	50.4 (4.8-135)
NO ₃ ⁻	0	22.1 (17.4-28.3)	45.7 (36.1-58.7)	71 (56-91.2)	550 (434-706)
<i>Nitric acid production</i>					
N ₂ O	0	0.2 (0.1-0.3)	0.3 (0.2-0.7)	0.5 (0.3-1.1)	3.9 (2.4-8.7)
<i>Gasoline road vehicles</i>					
N ₂ O	0	0.06 (0.03-0.12)	0.09 (0.06-0.2)	0.13 (0.08-0.3)	1.1 (0.7-2.5)
Combined	0	28.4 (19.6-42.8)	58.9 (40.6-88.7)	91.4 (62.9-138)	708 (489-1066)
Abatement costs (\$ billions)	2015	2020	2025	2030	Sum (2015-2030)
<i>N fertilizer and manure</i>					
	0	6.9 (0.6-13.2)	14.3 (1.1-27.6)	22.4 (1.7-43.2)	173 (13.8-332)
<i>Nitric acid production</i>					
	0	0.02 (0.003-0.04)	0.02 (0.004-0.06)	0.03 (0.005-0.07)	0.4 (0.1-0.9)
<i>Gasoline road vehicles</i>					
	0	0.002 (0.001-0.007)	0.004 (0.002-0.01)	0.006 (0.002-0.02)	0.05 (0.02-0.14)
Combined	0	6.9 (0.6-13.2)	14.4 (1.1-27.6)	22.4 (1.7-43.2)	173 (13.8-332)

523

524 **Table 6** The avoided damages and abatement costs (in \$2014 billions) of following the
525 mitigation scenario vs. the business-as-usual from 2015 to 2030, and summed over the
526 same period. The avoided damages are disaggregated by N compound and source, and
527 then combined. Similarly, the abatement costs are disaggregated by source and then
528 combined.

529

530 5.3 Discussion

531

532 It should be noted that because N₂O has global impacts as a GHG and ozone depleting

533 substance, the U.S. would reap only a portion of the environmental and health benefits

534 from reducing domestic N₂O emissions while being burdened with all the abatement

535 costs. Nevertheless, as the results demonstrate, it is the local co-benefits of N₂O reduction
536 that dominate (i.e. avoided N leaching, as well as NO_x and NH₃ emissions), and these
537 benefit almost exclusively the U.S. and its immediate neighbors.

538
539 While the environmental and economic benefits of reducing N₂O emissions (and N losses
540 more generally) are apparent, there are also challenges for policy-makers in addressing
541 this issue. One of the most considerable is the risk of pollution swapping i.e. measures
542 reducing one form of N pollution exacerbating another. For example, efforts to reduce N
543 leaching and run-off under the EU Nitrates Directive include the winter storage of
544 manures, which can increase NH₃ emissions. Indeed, Denmark and the Netherlands have
545 measured substantial increases in springtime NH₃ emissions as a result of their nitrate
546 policy (Erisman et al., 1998). Another example is how catalysts developed to reduce NO_x
547 emissions from mobile combustion have led to an increase in N₂O emissions in certain
548 cases (UNEP, 2013). Therefore, unless a more integrated approach to N pollution is taken
549 (which in agriculture, for example, requires reducing N losses at the source) we will
550 continue to “roll the dice” when it comes to policy: some measures may serendipitously
551 reduce several forms of pollution, while others may exacerbate one aspect of the problem
552 while purportedly solving another. Linked to this is the fact that N pollution occurs across
553 multiple temporal (days to decades) and spatial (field to continent) scales. Certain aspects
554 of N pollution impact local areas over relatively short periods of time (e.g. smog events
555 in urban areas, algal blooms in coastal regions), while others, such as N₂O, impact much
556 larger areas and timescales. Consequently, policy-makers should take these dynamics into
557 account when deciding which regions and sectors to focus on, prioritizing areas

558 particularly vulnerable to N losses and impacts (e.g. high population density, porous
559 soils, potential for groundwater contamination etc.).

560

561 **6. Conclusion**

562

563 In the absence of new legislation, measures to address climate change in the U.S. at the
564 federal level have to rely on existing legal authority. While various rules and initiatives
565 have been introduced to address a number of GHGs (notably CO₂, CH₄ and HFCs), N₂O,
566 the third most abundantly emitted GHG and the largest remaining threat to the
567 stratospheric ozone layer, has been mostly ignored. The unique chemistry of the N
568 cascade – where one N atom can be converted into a number of different chemical forms,
569 each with its own environmental impact – broadens the legal possibilities for addressing
570 this issue. Indeed, our legal analysis suggests that the Clean Air Act, and the authority to
571 regulate ozone-depleting substances in particular, could be the most promising legal
572 pathway for regulating N₂O across all sources. We illustrate that invoking this authority
573 and introducing measures to limit N₂O emissions could deliver important environmental
574 and economic benefits to society that go beyond the adverse stratospheric ozone and
575 climate impacts caused by N₂O. The benefits to water and air quality from reduced NH₃,
576 NO_x and NO₃⁻ losses are even more significant, demonstrating the large co-benefits that
577 addressing particular sources of climate warming and stratospheric ozone depletion could
578 deliver. Moreover, it is possible that addressing N pollution not only benefits the
579 environment, but also reduces farmer costs (due to more efficient fertilizer use) and
580 increases fertilizer industry profitability (via increased demand for enhanced efficiency

581 fertilizers and fertilizer services) (Kanter et al., 2015). Finally, in the wake of the Paris
582 Climate Agreement, the current focus on only a subset of GHGs will make it even more
583 challenging to keep global temperatures “well below” the 2°C target (Gernaat et al.
584 2015). Consequently, all mitigation opportunities need to be considered, including
585 measures related to N₂O. Such measures, if devised and implemented accordingly, could
586 be an excellent vehicle for reducing many of the adverse environmental and health
587 impacts N pollution exacerbates across the U.S. and the world.

588

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