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

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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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1. Introduction

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

The regulations and targets that followed put limits on carbon dioxide (CO_2) emissions from coal-burning power plants, while other initiatives (such as a bilateral agreement with Canada in March 2016) aim to reduce methane (CH_4) emissions from natural gas installations and pipelines. At the same time, the U.S. partnered with Canada and Mexico to propose an amendment to the 1987 Montreal Protocol that would phase down the production and consumption of hydrofluorocarbons (HFCs). While these approaches cover several of the major sources of U.S. GHG emissions, they do not cover them all. And if the international community is to meet the temperature goal outlined in the Paris Climate Agreement – to "hold the increase in global average temperature to well below $2^{o}C$ and to pursue efforts to limit the temperature increase to $1.5^{o}C$" (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 (N_2O). 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 N_2O 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 CO_2 equivalents (CO_2e), N_2O 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. CO_2e 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). N_2O 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, N_2O 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   volatized 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).

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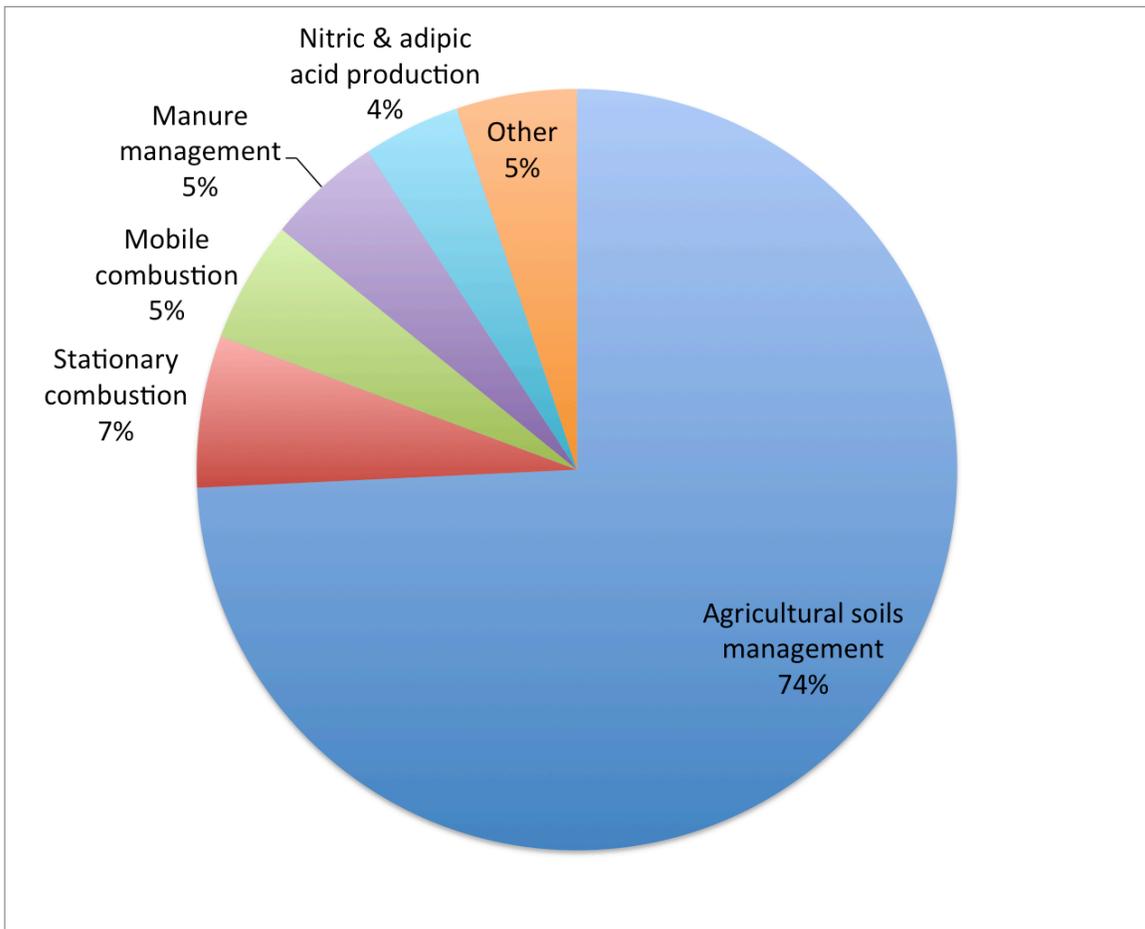
Figure 1 Anthropogenic N_2O emission sources in the U.S. in 2013. The dominant source is agricultural soils management, which includes emissions from mineralization, asymbiotic fixation, fertilizer and manure use, crop residues and sewage sludge (adapted from USEPA, 2015a).

While the N cascade is the subject of a large and growing scientific literature, it has yet to receive the same level of attention from legal scholars, despite being ripe for analysis. The multitude of impacts that one atom of N can create gives environmental policy-makers several legal options to how to manage it: existing environmental law related to air and water pollution, biodiversity preservation, climate change and stratospheric ozone depletion could all be justifications for addressing various sections of the N cascade. And because of the tightly coupled nature of the N cycle, efforts to reduce one particular

144   component of the N cascade could impact N_2O emissions as well. Conversely, efforts to

145   reduce N_2O 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 NO_3^- 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 NH_3 by 3%, N_2O 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 N_2O 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 N_2O 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 N_2O 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 N_2O 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 N_2O 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 N_2O emissions on a nation-wide scale, and whether it could be used to

178   regulate all major sources of N_2O 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 N_2O 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 N_2O-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 N_2O emissions.

186

187   Using this framework, we evaluated opportunities to reduce N_2O 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 N_2O 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 N_2O 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 N_2O emissions

200   from major sources. Similarly, we concluded that existing state programs do not establish

201   clear mandates or authorizations to regulate N_2O 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 N_2O

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 CO_2 emissions from new and existing power

210   plants, and GHG emissions from motor vehicles. The USEPA also recently proposed a

211   rule to reduce CH_4 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 N_2O emissions from any sources other than motor vehicles. Moreover, the N_2O

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 N_2O 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 N_2O emissions from stationary sources, and Section 202 to regulate N_2O

225   emissions from mobile sources. Finally, USEPA could determine that N_2O emissions

226   contribute to international air pollution under Section 115 and use its authority under that

227   section to compel state regulation of N_2O emission sources. Table 1 compares the

228   different provisions under the Clean Air Act that could be used to address N_2O.

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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 N_2O emissions. N_2O
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 N_2O 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 N_2O 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 N_2O 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 N_2O) and a mitigation scenario

255 (where a concerted effort is made to reduce N_2O). For the business-as-usual scenarios, we

256 use N_2O emission projections from the EPA report "Global Mitigation of Non-CO_2

257 Greenhouse Gases: 2010-2030" (USEPA, 2013a).

258

259 *3.1 Agricultural emissions*

260 Agricultural soil management is the single largest source of N_2O emissions in the US,

261 responsible for 74% of N_2O emissions, and 4% of total US GHG emissions in 2013

262 (USEPA, 2015a). Disaggregating agricultural N_2O 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 N_2O to Protect Climate and the Ozone Layer", which assumes that an increase in

298 fertilizer use efficiency reduces fertilizer demand by 15% and the N_2O 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 N_2O

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 N_2O emissions (Akiyama et al., 2010, Abalos et al., 2014). For N_2O

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 N_2O 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
BAU scenario				
N_2O EF fertilizer (%)	1.5	1.5	1.5	1.5
N_2O 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
MIT scenario				
N_2O EF fertilizer (%)	1.5	1.4	1.3	1.2
N_2O 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 N_2O 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 N_2O – and a mitigation (MIT) scenario, where a concerted effort is made
321   to reduce N_2O. The mitigation scenario is based on the Case 3 scenario in UNEP (2013).
322   The emission factors include both direct N_2O 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 N_2O 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 NH_3 and NO_x, Ogle et al. (2014) estimates that

332   10% of synthetic fertilizer N and 20% of manure N is volatilized as NH_3 and NO_x (with

333   NH_3 dominating). Of this, 1% is subsequently transformed into N_2O. 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 N_2O.

338

339   *3.2 Non-agricultural emissions*

340   Non-agricultural sources are responsible for 20% of anthropogenic N_2O 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 N_2O 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 N_2O in the US – adipic acid production – already have N_2O abatement

349   technology installed (USEPA, 2015a). While newer technologies exist that can reduce

350   N_2O 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 N_2O 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 N_2O emissions. However, there are

358   fewer opportunities to reduce N_2O emissions from this sector, because most of the coal-

359   fired power plants in the US are pulverized coal plants boilers, which emit less N_2O than

360   facilities with more modern technologies (such as fluidized bed combustion) even when

361   those facilities install N_2O abatement technologies (USEPA, 2015a). Thus, we do not

362   consider N_2O 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 N_2O emissions from

365   non-agricultural sources, and thus about 7% of total anthropogenic N_2O emissions in the

366   U.S.

367

368   The business-as-usual scenario from EPA (2013a) projects a 10% decrease in US N_2O

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 N_2O 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 N_2O abatement technology, up from 28% today (USEPA,

375   2015a). This implies that by 2030 average N_2O emissions from nitric acid production

376   decrease from 7kg to approximately 0.1 kg N_2O 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 N_2O emission caps from 0.01 g N_2O/mile to 0.0036 g N_2O/mile for

382   gasoline passenger cars and 0.0066 g N_2O/mile for gasoline light-duty trucks. For heavy-

383   duty trucks it would mean reducing the emissions cap from 0.05 g N_2O/mile to 0.0134 g

384   N_2O/mile. This would require the accelerated diffusion of a range of market-ready

385   advanced three-way catalysts that have significantly lower N_2O 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 N_2O 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 NH_3 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 N_2O 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	*Birch et al. 2010*	*Compton et al. 2010*	*Gu et al. 2012*	*Van Grinsven et al. 2013*	**Average**
N_2O	-	**$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	*Sutton et al. 2013*	*Kanter et al. 2015*	*Laboski et al 2006; Roberts et al. 2014*	*EPA 2013*
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)

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

* Uncertainty ranges not reported.

459 In terms of non-agricultural N_2O 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 N_2O-N yr^{-1} by 2030 (Table

471 4, Figure 2). Much of the reduction in N_2O 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 CO_2e 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 CO_2e 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 N_2O-N, equivalent to 449 Mt CO_2e 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 NH_3 losses

484 by 0.4 Mt N yr^{-1} each, and NO_3^- losses by 1.4 Mt NO_3-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 NH_3, and

486 11.1 Mt NO_3-N for NO_3^- (Table 4). Figure 2 compares the total N_2O reductions under the

487 mitigation scenario and business as usual.

|	2015	2020	2025	2030	Sum (2015-2030)
N_2O (Mt N yr^{-1})	0	0.05	0.11	0.16	1.26
Climate (Mt CO_2e yr^{-1})	0	24	49	74	449
Ozone (kt ODP yr^{-1})	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_2O-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
Total	*BAU*	*0.34*	*0.36*	*0.37*	*0.38*
	MIT	*0.34*	*0.31*	*0.26*	*0.22*

493 **Table 5** N_2O 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
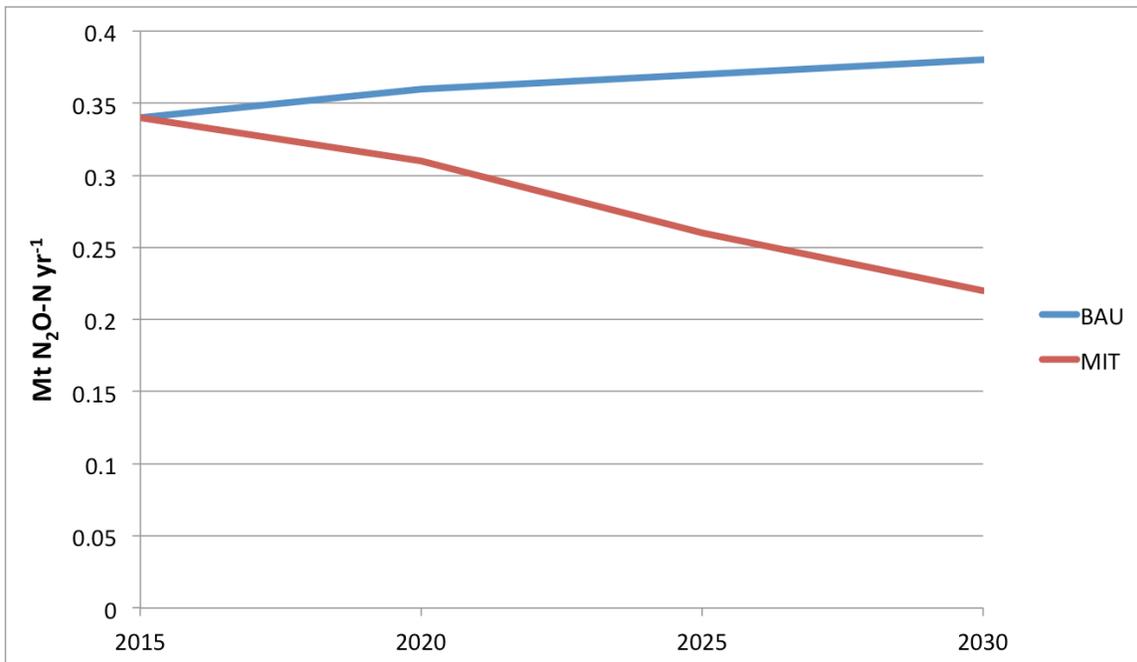
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499 **Figure 2** – U.S. N_2O emission trends from the sources considered in this study (nitrogen
500 fertilizer and manure use, gasoline-powered road vehicles, and nitric acid production)
501 over 2015-2030 in a business-as-usual versus a mitigation 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 N_2O emissions reductions constitute only 2% of this overall

507 amount, with the bulk of the benefits coming from reductions in other N compounds –

508 NO_3^- in particular, given both the higher absolute reductions and damage costs per

509 kilogram. This demonstrates the importance of considering the N_2O 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 N_2O emissions, society is

521   projected to gain $4.10.

522

Avoided damages ($ billions)	2015	2020	2025	2030	Sum (2015-2030)
N fertilizer and manure					
N_2O	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)
Nitric acid production					
N_2O	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)
Gasoline road vehicles					
N_2O	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)
N fertilizer and manure	0	6.9 (0.6-13.2)	14.3 (1.1-27.6)	22.4 (1.7-43.2)	173 (13.8-332)
Nitric acid production	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)
Gasoline road vehicles	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)

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

5.3 Discussion

It should be noted that because N_2O has global impacts as a GHG and ozone depleting substance, the U.S. would reap only a portion of the environmental and health benefits from reducing domestic N_2O emissions while being burdened with all the abatement

535   costs. Nevertheless, as the results demonstrate, it is the local co-benefits of N_2O reduction

536   that dominate (i.e. avoided N leaching, as well as NO_x and NH_3 emissions), and these

537   benefit almost exclusively the U.S. and its immediate neighbors.

538
539   While the environmental and economic benefits of reducing N_2O 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 NH_3 emissions. Indeed, Denmark and the Netherlands have

545   measured substantial increases in springtime NH_3 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 N_2O 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 N_2O, 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 CO_2, CH_4 and HFCs), N_2O,

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 N_2O across all sources. We illustrate that invoking this authority

573 and introducing measures to limit N_2O emissions could deliver important environmental

574 and economic benefits to society that go beyond the adverse stratospheric ozone and

575 climate impacts caused by N_2O. The benefits to water and air quality from reduced NH_3,

576 NO_x and NO_3^- 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^oC target (Gernaat et al.

584   2015). Consequently, all mitigation opportunities need to be considered, including

585   measures related to N_2O. 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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