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Representative concentration pathways and mitigation scenarios for nitrous oxide

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Abstract

The challenges of mitigating nitrous oxide (N_2O) emissions are substantially different from those for carbon dioxide (CO_2) and methane (CH_4), because nitrogen (N) is essential for food production, and over 80% of anthropogenic N_2O emissions are from the agricultural sector. Here I use a model of emission factors of N_2O to demonstrate the magnitude of improvements in agriculture and industrial sectors and changes in dietary habits that would be necessary to match the four representative concentration pathways (RCPs) now being considered in the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). Stabilizing atmospheric N_2O by 2050, consistent with the most aggressive of the RCP mitigation scenarios, would require about 50% reductions in emission factors in all sectors and about a 50% reduction in mean per capita meat consumption in the developed world. Technologies exist to achieve such improved efficiencies, but overcoming social, economic, and political impediments for their adoption and for changes in dietary habits will present large challenges.

Keywords: climate change, greenhouse gases, nitrous oxide, N_2O, representative concentration pathways, RCPs

1. Introduction

Nitrous oxide is the third most important anthropogenic greenhouse gas (Forester *et al* 2007) and the most important anthropogenic contributor to stratospheric ozone destruction (Ravishankara *et al* 2009). Because no biological system can be made completely efficient, it is inevitable that N_2O will ‘leak’ from the nitrogen cycling processes (Firestone and Davidson 1989) that have been accelerated to feed more than 7 billion people. However, the fraction of N cycling through agricultural systems that leaks to the atmosphere as N_2O can be minimized through efficient nutrient management (Adviento-Borbe *et al* 2007, Ribaudo *et al* 2011, Snyder *et al* 2009). In the developed world, crop N use efficiency (NUE; percentage of applied N taken up by the crop) seldom exceeds 50%, and it is generally substantially less in the developing world (IFA 2007). Efficiencies are further reduced when crops are used as animal feed, because only a small fraction of the N ingested by livestock is consumed by humans. Considering the food chain and waste that occurs from the farm to the dinner table (Popp *et al* 2010), humans generally eat less than 15% of the N that enters croplands (Galloway *et al* 2010, Leach *et al* 2012). Meeting the nutritional needs of a growing human population will likely create more demand for use of synthetic N fertilizers and greater risk of increasing N_2O emissions (Reay *et al* 2012, Smith *et al* 2008).

A combination of top-down and bottom-up modeling of global N_2O sources and sinks has demonstrated that globally averaged emission factors (EFs) can be used to estimate N_2O emissions from the agricultural sector since the industrial revolution. In one study (Smith *et al* 2012), annual N_2O emissions estimated as a 4% EF of annual newly fixed or mobilize N, which includes Haber–Bosch synthesis of N fertilizers, biological N fixation by leguminous crops, and mining of soil N when native soils are tilled, was shown to reproduce the historic increase in atmospheric N_2O. In another study (Davidson 2009), the source was partitioned

Table 1. Changes in mean global daily caloric intake and population based on projections by FAO (2006).

Year	Mean caloric intake kcal person^{-1} day^{-1}	Population millions	Global caloric intake kcals × 10^9 day^{-1}	Increase relative to 2000
2000	2789	6071	16 932	1.00
2015	2950	7197	21 231	1.25
2030	3040	8130	24 715	1.46
2050	3130	8919	27 916	1.65

into two components, with EFs of annual N_2O emissions as 2.0% of annual global synthetic fertilizer-N use and 2.5% of annual global manure-N production. These two approaches work equally well, because the historical growth of livestock herds and tillage of native soils are confounded. Furthermore, much of the crop production of newly tilled land was fed to animals (David *et al* 2001), so that much of the N mobilized by soil tillage passed through the manure. These EFs differ from the IPCC tier 1 default emission factors because they also include all indirect downwind and downstream emissions attributable to agricultural use of N, including those from human sewage (Davidson 2009). None of these EFs perform reliably at the plot scale, because of large spatial and temporal variability in factors that affect emissions, but they have been shown to converge for relatively consistent global estimates (Del Grosso *et al* 2008, Reay *et al* 2012). The average NUE has improved in the developed world since the 1970s (IFA 2007), which may have lowered N_2O EFs there, but low NUE and high EFs in expanding agriculture of the developing world may effectively cancel this progress with respect to a global average. Here, I assume that it is possible that the global average EFs can be lowered through improved management of both fertilizer and manure sources and that dietary choices regarding meat consumption also affect N_2O emissions through their effect on fertilizer demand and manure production.

The IPCC-AR5 has adopted a series of four representative concentration pathways (RCPs) as examples of a range of scenarios of internally consistent future projections of the major greenhouse gas emissions (Van Vuuren *et al* 2011a). There are many combinations of cultural and technological scenarios that could be consistent with each of these RCPs. The four integrated assessment models that generated the RCPs are not meant to define the only unique scenarios for analysis, but rather to produce a range of possible pathways of changes in greenhouse gas emissions depending on development scenarios. Here I compare the four RCPs for N_2O with an analysis of the magnitude of global-scale reductions in emission factors for N_2O in agriculture, changes in dietary preferences, and N_2O mitigation in other sectors that would be necessary to achieve N_2O concentration pathways consistent with each AR5 RCP. While other studies have focused on specific approaches to reducing N_2O emissions (Davidson *et al* 2012, Ribaudo *et al* 2011, Smith *et al* 2008, Snyder *et al* 2009) and others have noted the overall challenge (Erisman *et al* 2008, Galloway *et al* 2008, Reay *et al* 2012), the scale of the improvements needed to match the four RCPs has not been evaluated.

2. Methods

Scenarios of future demand for meat and crop commodities require assumptions about population growth and nutritional status. I adopt the somewhat optimistic assumptions of the Food and Agriculture Organization (FAO 2006) that nutrition will improve in the countries that currently have over 40% of their population malnourished, dropping to only 10% by 2050. The expected 2050 human population of 8.9 billion is projected to have average daily per capita caloric intake of 3130 kcal, up from 2790 kcal in 2000. Per capita meat consumption in the developing world is assumed to increase from 28 kg yr^{-1} in 2002 to 37 kg yr^{-1} in 2030. Less progress in alleviating poverty and poor nutrition could mean less demand for agricultural products and lower N_2O emissions. This FAO report also projects that meat consumption in the developed world will increase from 78 kg yr^{-1} in 2002 to 89 kg yr^{-1} in 2030.

This baseline scenario of population growth and food consumption patterns becomes the first of the five scenarios for projected N_2O emissions: (1) FAO population/diet scenarios (FAO 2006) with factors for N_2O emissions (Davidson 2009) attributable to fertilizer-N (2.5%) and manure-N (2.0%), with no major improvements in efficiencies; (2) same as #1, but per capita meat consumption in the developed world declines to 37 kg yr^{-1} by 2030 (which is approximately half the level consumed in 1980), thus reducing manure-N production and fertilizer-N use by 21% relative to scenario 1; (3) same as #1, but improvements in nutrient and manure management reduce the emission factors by 50% by 2050; (4) same as #3, but industrial, transportation and biomass burning emissions are similarly reduced by 50% by 2050; and (5) scenarios 2 and 4 combined.

2.1. Scenario 1—FAO projections with business-as-usual mitigation

Using FAO projections (FAO 2006) of population growth and per capita consumption of calories and animal products, I scaled future fertilizer use to projected mean daily global caloric intake as shown in table 1, using 86 Tg N yr^{-1} as the benchmark global fertilizer consumption value for the year 2000. This projection is compared to other independent N fertilizer projections in table 2. The fertilizer projections developed here by scaling to projected caloric intake are generally consistent with the high scenario of an earlier study of the FAO (2000), but lower than the projections of a later study (FAO 2008) and the projection for 2014 by the

Table 2. Past and projected N fertilizer use (Tg N yr^{-1}) based on scaling with caloric intake (this study, see table 1) and three independent sources.

Year	Based on caloric intake (this study)	FAO (2000) low scenario	FAO (2000) mid-scenario	FAO (2000) high scenario	FAO (2008)	IFA (2010)
2000	86[a]	78[b]	78[b]	78[b]	91[c]	NA
2015	107	88	100	106	115	112[d]
2030	127	96	118	125	137	NA
2050	141	NA	NA	NA	NA	NA

[a] Davidson (2009).
[b] Estimate for 1995–7.
[c] Estimate for 2005.
[d] Estimate for 2014.

International Fertilizer Association (IFA 2007). They are also consistent with the intermediate scenarios of Erisman *et al* (2008), based on their projections of N fertilizer demand that would be consistent with the storylines of the IPCC Special Report on Emission Scenarios (Nakicenovic and Swart 2000). Therefore, I consider this to be an intermediate estimate for 2015 and 2030. Projections for 2050 are much more variable, ranging from 110 to 170 Tg N yr^{-1} (IFA 2007), with the projection here of 141 again being near the middle of this range.

The annual estimates of fertilizer use from 2000 to 2050 were interpolated by applying a polynomial fit to the values in the two left-most columns of table 2: fertilizer-N (Tg N yr^{-1}) $= -0.00991\ (yr)^2 + 41.25\ (yr) - 42\,770$; $R^2 = 0.99$. These fertilizer consumption estimates were then used in equation (1) below.

Projections of manure production were assumed to be proportional to FAO (2006) projections of global meat consumption, which is expected to increase by 1.7% annually until 2030 and then 1.0% annually thereafter until 2050 (global milk and dairy production are expected to grown at similar rates: 1.4% and 0.9% for 2000–30 and 2030–50, respectively). Following these projected rates of meat production growth, N in global livestock manure production would increase from 139 Tg N yr^{-1} in 2000 to 230 Tg N yr^{-1} in 2030 and to 281 Tg N yr^{-1} in 2050. These manure production estimates and interpolated yearly values were then used in equation (1) below.

2.2. Scenario 2—reduced meat consumption

The FAO projects growth in per capita meat consumption in both developed and developing countries, as shown in table 3. For the 'less meat' scenario, I assume that mean per capita meat consumption in the developing world will continue to increase as shown in table 3, but that it will decline to 50% of the 1980 level of 73 kg in the developed world by 2030 and then remain constant to 2050. This would bring per capita meat consumption to nearly equivalent levels in the developed and developing world at about 37 kg in 2030. Of course, these are averages which hide variation among and within countries in these two broad categories. The net effect is a reduction in total global meat production by 21%. For this less meat scenario, I scale back manure production and fertilizer use by 21% in 2030 and 2050 relative to the projections of scenario 1. This may be an overestimate of decline in manure production, because it does not account for substitution of dairy products for meat. Similarly, while less fertilizer would be needed to grow grain for livestock feed, some additional vegetable sources of calories and protein may need to be grown for direct human consumption. On the other hand, mean per capita protein and caloric requirements are currently exceeded in North America and Western Europe, so these substitutions are not necessary for nutritional purposes or inevitable. The objective here is not that highly accurate predictions of the agricultural implications of a major change in dietary habits in the developed world can be made, but rather that a first cut at assessing the scale of the possible mitigation effect for N_2O of a major hypothetical shift in dietary preferences is possible.

Table 3. Past and future mean annual per capita meat consumption and total annual global meat consumption in developing and developed countries (from FAO 2006).

	Per capita meat consumption (kg)		Total meat consumption (millions of tons)	
Year	Developing	Developed	Developing	Developed
1980	14	73	47	86
1990	18	80	73	100
2002	28	78	137	102
2015	32	83	184	112
2030	37	89	252	121

2.3. Scenario 3—improved agricultural efficiency

For this scenario, it is assumed that the emission factors from N fertilizers (F_f) and manure (F_m) will incrementally decrease each year between now and 2050, ending at values of 0.0127 and 0.010 25, respectively. This represents a phase in of improved efficiency of fertilizer and manure management to reduce N_2O emission factors by 50%. These annually decreasing emissions factors were substituted in equation (1).

2.4. Scenario 4—improved efficiency in all sectors

This scenario is the same as scenario 3, except that the emissions from transportation/industrial sectors and from biomass burning also decline incrementally until they reach

Table 4. Projected global anthropogenic N_2O production (Tg N_2O–N yr^{-1}) from all sectors for the five scenarios of this study.

Year	S1. FAO projections, BAU mitigation	S2. Less meat consumption in developed world	S3. Agricultural efficiency improvement	S4. Agricultural and industry efficiency improvement	S5. Combination of S2 and S4.
2000	6.3	6.3	6.3	6.3	6.3
2015	7.8	6.8	7.2	7.1	6.2
2030	9.2	7.5	7.2	6.9	5.6
2050	10.6	8.6	6.0	5.3	4.4

values of 0.4 Tg N yr^{-1} and 0.25 Tg N yr^{-1}, respectively, in 2050. This represents a 50% reduction in emissions from these sectors from the baseline scenario.

2.5. Scenario 5—combined scenarios

This scenario combines reduction in meat consumption described in scenario 2 with the all-sector efficiency improvements described in scenario 4.

2.6. Calculations of atmospheric N_2O concentrations

I used the same model structure described in detail in the supplemental information published with Davidson (2009). Briefly, the annual increase in the atmospheric burden of N_2O can be calculated from the following anthropogenic sources and sinks that have changed the natural balance since the industrial revolution as follows:

$$\begin{aligned}\text{Atmospheric increase} &= \text{anthropogenic biological source}\\ &+ \text{biomass burning} + \text{industrial and transport sources}\\ &- \text{reduced natural tropical forest soil source}\\ &- \text{anthropogenic stratospheric sink.}\end{aligned} \quad (1)$$

Based on that previous analysis, I assume here the following terms for the above equation:

$$\text{Anthropogenic biological source} = F_{\mathrm{m}}^{*}\text{manure} - N + F_{\mathrm{f}}^{*}\text{fertilizer} - N,$$

where $F_{\mathrm{m}} = 0.0203$, which is the fraction of annual manure-N production emitted as N_2O, and $F_{\mathrm{f}} = 0.0254$, which is the fraction of annual synthetic fertilizer-N production emitted as N_2O. Note that these fractions are modified in scenario 3.

Biomass burning = 0.5 Tg N_2O–N yr^{-1}. Note that this value decreases in scenario 4.

Industrial and transportation sectors = 0.8 Tg N_2O–N yr^{-1}. Note that this value decreases in scenario 4.

Reduced soil source due to historic tropical deforestation = 1.0 Tg N_2O–N yr^{-1}.

Anthropogenic stratospheric sink (Tg N_2O–N yr^{-1}) = $1.7 \times [(N_2O_t - 270)/45.7]$ where N_2O_t is the atmospheric N_2O concentration (ppb) in year t; 1.7 Tg N_2O–N yr^{-1} is the increased stratospheric sink in 2000 relative to the pre-industrial sink of 10.2 Tg N_2O–N yr^{-1}; 270 ppb is the pre-industrial N_2O concentration when the natural sources and sinks were in approximate balance; and 45.7 ppb is the increase in atmospheric N_2O between pre-industrial times and 2000 (Crutzen *et al* 2008, Prather *et al* 2001). Equation (1) was then used to generate anthropogenic N_2O production and growth of the atmospheric burden of N_2O through 2050 for each of the five scenarios.

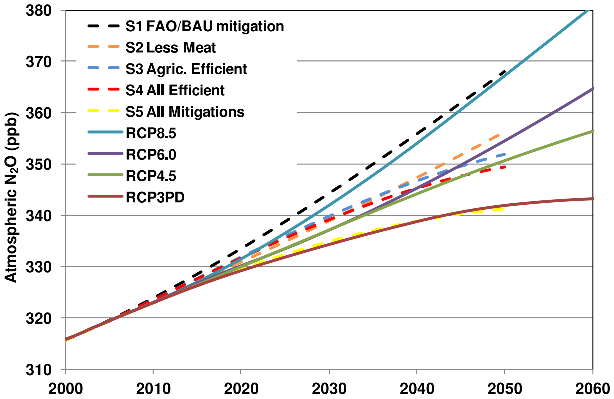

Figure 1. Projected atmospheric N_2O concentrations for the four IPCC-AR5 representative concentration pathways (RCPs) and the five scenarios of this study. S1 = FAO population and dietary projections with no new N_2O mitigation efforts; S2 = same as S1 but also 50% reduction in mean per capita meat consumption in the developed world by 2030 relative to 1980 consumption; S3 = same as S1 but improvements in agricultural efficiencies that reduce N_2O emissions factors for N fertilizers and manure by 50% by 2050; S4 = same as S3 but also 50% emission reductions in industry and transportation sectors and by biomass burning; S5 = combination of S2 and S4.

3. Results and discussion

The annual global anthropogenic N_2O production estimates for each of the five scenarios are shown in table 4, and the resulting atmospheric N_2O concentrations are compared to the four IPCC-AR5 RCPs in figure 1. The RCPs are named according to the resulting total radiative forcing in 2100 (e.g., RCP8.5 indicates 8.5 W m^{-2} radiative forcing due to anthropogenic greenhouse gases). One of the RCPs has two names (RCP2.6 and RCP3PD), because it projects 2.6 W m^{-2} radiative forcing in 2100, but with a mid-21st-century 3.0 W m^{-2} peak and subsequent decline (3PD).

All of these RCP and scenario projections of N_2O concentrations are subject to large uncertainties associated with assumptions about population growth, poverty, dietary habits, fertilizer use, manure production and emission factors. However, this analysis frames the magnitude of the problem and its potential solutions. It demonstrates that N_2O

concentrations will continue to increase mostly unabated unless major improvements in agricultural efficiencies and/or significant changes in dietary habits of the developed world are achieved. The RCP8.5 (Riahi *et al* 2011), with a slight acceleration of the rate of increase in atmospheric N_2O concentrations, is a reasonable representation of expected N_2O concentrations with growing agricultural production to feed a growing and better nourished population, but without major new improvements in agricultural efficiencies (scenario 1). The RCP6.0 (Masui *et al* 2011), with slower concentration growth rates but no leveling off before 2100, might be achievable if the developed world cuts per capita meat consumption by about 50% from 1980 levels (scenario 2) or if major improvements in agricultural efficiencies on the order of 50% are realized (scenario 3). The RCP4.5 (Thomson *et al* 2011), with slower concentration growth rates resulting in some flattening of the curve, might be achievable if, in addition to the agricultural efficiencies needed for RCP6.0, the emissions from transportation, energy, industrial and biomass burning sectors are also decreased by about 50% (scenario 4). Only if all of these major changes in efficiencies and diet are realized (scenario 5) could RCP3PD (Van Vuuren *et al* 2011b) be achieved with its stabilization of atmospheric N_2O concentrations of about 345 ppb by 2050. Although radiative forcing of the RCP3PD scenario is projected to decline to 2.6 $W\ m^{-2}$ by 2100, this is due primarily to simulated declines in CO_2 and CH_4 and not N_2O emissions beyond 2050 (Van Vuuren *et al* 2011b). The integrated assessment model that produced RCP3PD is the most optimistic of the RCPs, but even it projects continued elevated N_2O concentrations in 2050 and beyond due to continued high demand for food and biofuels. The present study reinforces the difficulty we face to stabilize atmospheric N_2O below 350 ppb, let alone contemplate reducing atmospheric N_2O concentrations as long as 9–10 billion people must be fed.

Reducing per capita meat consumption by 50% in the developed world seems unlikely under current cultural trends. On the other hand, large reductions in smoking have been witnessed during recent decades, suggesting that a major change in human behavior is possible over a similar time frame. Reducing obesity and related per capita meat consumption in the developed world could also have salutary health effects (Reay *et al* 2011), although they are not always as obvious or compelling as the risks avoided by stopping smoking. A significant portion of the needed decrease in per capita meat and dairy production could be accomplished by avoiding food wastage (Popp *et al* 2010, Reay *et al* 2012). This analysis does not include shifting meat consumption from beef to pork, poultry or fish, which have lower N footprints (Leach *et al* 2012, Bouwman *et al* 2011). It is possible that manure production and concomitant N_2O emissions could decrease while per capita meat consumption remained relatively constant if dietary preferences shifted away from red meat. Similarly, the global averages used here mask important regional differences that could present both difficulties and opportunities to change dietary habits and mitigation of emissions from animal production systems.

Nor does this analysis include the highly uncertain projections of expanding biofuel production as an additional demand for use of N fertilizers. At present, about 78% of global ethanol production comes from about 11 million ha of maize production in the US and about 8 million ha of sugarcane production in Brazil (OECD/FAO 2011). About half of global biodiesel production comes from about 7 million ha of oilseed production in the European Union (OECD/FAO 2011). Based on average N fertilizer application rates for these crops in these regions (Smeets *et al* 2009), I estimate that about 3 Tg of annual fertilizer-N use is devoted to these biofuels crops, resulting in about 0.06 $Tg\ yr^{-1}$ N_2O–N emissions. Accounting for production of other biofuels crops in other regions, the total global emissions due to biofuels crops are likely to be about 0.1 $Tg\ yr^{-1}$ N_2O–N, which is a small fraction of current anthropogenic N_2O emissions (table 4). Therefore, even if ethanol production increases by 50% and biodiesel production doubles by 2020, as projected (OECD/FAO 2011), the increase in N_2O emissions will be modest relative to emissions from increasing food demand. On the other hand, some scenarios of biofuel production expansion to 2050 and 2100 project much larger increases in fertilizer-N devoted to biofuels production (Erisman *et al* 2008, Melillo *et al* 2009, Van Vuuren *et al* 2011b). However, fertilizer-N demands are likely to be much smaller for second-generation cellulosic-based fuels than for current first-generation liquid transport fuels (Erisman *et al* 2010, Reay *et al* 2012), so there are large uncertainties in both the projections of biofuels production and the attendant demand for fertilizer-N. In one projection (Erisman *et al* 2008), demand for N fertilizers due to expansion of biofuels was estimated to increase by 70 Tg N by 2100, assuming an average application rate of 100 kg $N\ ha^{-1}$, which is less than current mean application rates for US maize, but more than for many potential cellulosic crops. If fertilizer demand increased by 70 Tg N due to biofuel production demand and if overall emission factors remained unchanged, the additional 1.4 Tg N_2O–N yr^{-1} production would cancel most of the mitigation calculated for change in dietary habits shown in table 4.

The needed technologies to improve NUE in crop and animal production systems and to reduce N_2O emissions are known, and in many cases have been demonstrated (Adviento-Borbe *et al* 2007, Davidson *et al* 2012, Ribaudo *et al* 2011, Smith *et al* 2008, Snyder *et al* 2009), such as improved timing of fertilizer application to match crop demand, the use nitrification inhibitors and winter cover crops, and improved livestock nutrition. In the present analysis, I represented improved agricultural efficiencies only as reductions in N_2O EFs, but improving NUE could have double benefits of both lowering EFs and reducing fertilizer demand. Erisman *et al* (2008) projected that N fertilizer use could be reduced by 40–60 $Tg\ yr^{-1}$ by 2100 by improved NUE while still meeting food demands. The additional costs, a lack of sufficient agricultural extension services, and the absence of political will for implementation remain major impediments to the adoption of technologies and practices that would increase NUEs and reduce N_2O EFs. Because N_2O is only one form of N that leaks out of agricultural systems, improved NUE would also yield significant co-benefits to N_2O mitigation for climate change and stratospheric ozone protection, such as improved drinking water quality, improved air quality, reduced loss of biodiversity in eutrophied aquatic and terrestrial ecosystems, and multiple economic benefits (Brink *et al* 2011, Davidson *et al* 2012).

The purpose here is not to be prescriptive in identifying which mitigation strategies should be followed, but rather to demonstrate the magnitude of changes needed to stabilize atmospheric N_2O concentrations while also improving the diets of the growing global human population. The RCPs of the IPCC-AR5 are reasonable projections of a range of scenarios, from little new mitigation to very aggressive goals in all sectors and in dietary preferences. There is no silver bullet for stabilization of atmospheric N_2O. Rather, meeting this challenge will require simultaneous large improvements in agricultural efficiencies, diet modification, and other sector emission reductions.

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