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Building on Paris: integrating nitrous oxide mitigation into future climate policy☆

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Nitrous oxide (N_2O) is an important contributor to climate change and stratospheric ozone depletion and yet it receives little attention in either the global climate or ozone agreements. More concerted efforts to address N_2O could be key in meeting the 2°C target and a suite of Sustainable Development Goals. The past several years has seen major advances in N_2O science and technology: our ability to estimate and simulate current and future N_2O emissions has improved, and more effective mitigation practices and technologies continue to arrive on the market. Moreover, nitrogen's unique chemistry means that reducing N_2O emissions could simultaneously address a number of other environmental threats exacerbated by N losses, further enhancing the cost-effectiveness of mitigation. Consequently, future National Determined Contributions under the Paris Climate Agreement could use this new knowledge to develop national N_2O targets that would help the international community meet its climate and sustainable development commitments.

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Introduction

Nitrous oxide (N_2O) poses a serious threat to the climate and the stratospheric ozone layer. It is the third most abundantly emitted greenhouse gas (GHG) after carbon dioxide (CO_2) and methane (CH_4), responsible for 6% of CO_2-equivalent emissions in 2014 [1]. N_2O is also the largest remaining threat to the stratospheric ozone layer given the global phase-out of chlorofluorocarbons (CFCs) and other ozone depleting substances [2]. Its atmospheric abundance has increased steadily since the turn of the century at approximately 0.25% per year. The key driver is a rise in reactive nitrogen (N) in the biosphere (any form of N other than atmospheric dinitrogen – N_2), largely from the application of synthetic fertilizer and manure for food production [3]. Other N_2O emissions sources include industry, energy, transport and wastewater [4]. Ambitious N_2O mitigation could avoid greenhouse gas emissions equivalent to 5%–10% of the remaining carbon budget for a 2°C world, and ozone losses comparable to the depletion potential of the global stock of CFCs in old refrigerators, air conditioners, insulation foams and other units [5,6•].

However, despite growing acknowledgement of N_2O's important contributions to these critical issues, it has been largely ignored in policy circles. Several reasons are often cited: the difficulty of monitoring agricultural emissions, which are the dominant source of anthropogenic N_2O; the lack of mitigation practices and technologies that are effective across multiple land-use types, climates and cultures; the mitigation costs compared to other GHG emission sources; the political power of farmer lobbies often resistant to environmental protection measures; and the essential role that nitrogen (N) plays in food production [7]. As a result, N_2O is rarely discussed in national or international climate and ozone negotiations. Indeed, while N_2O is one of six GHGs targeted under the United Nations Framework Convention on Climate Change (UNFCCC), most country plans (or Nationally Determined Contributions, NDCs) submitted to the Paris Climate Agreement (signed on December 15, 2015; entered into force November 4, 2016) specify broad measures that only tangentially affect N_2O emissions. Some Parties to the UNFCCC, such as the European Union, have considered N_2O as part of their overall GHG target development [8], but only one country, Uruguay, includes explicit mitigation targets for N_2O.

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And yet, addressing N_2O would not only deliver direct ozone and climate benefits – better nitrogen (N) management practices could also influence the mitigation potential of important strategies such as bioenergy production and soil carbon sequestration [4,9]. Furthermore, improving the efficiency of N use would decrease demand for Haber–Bosch N, the industrial synthesis of ammonia at the heart of modern fertilizer production, and could thus reduce GHG emissions considerably, given that the Haber–Bosch process is currently responsible for 1.4% of global CO_2 emissions and 1% of global energy consumption [10]. Finally, and perhaps most importantly, reducing reactive N losses and the associated cascade effect of N in the environment means that addressing N_2O with a holistic approach could deliver significant local co-benefits from air and water pollution abatement that vastly outweigh the global benefits from an economic perspective [6•,11].

Scientific research on N_2O – from better constraining sources, to more accurate emission rates and effective mitigation technologies – has advanced considerably over the past decade. This article describes the latest policy-relevant advances, their implications for climate policy development, and what a more focused approach to N_2O in future NDCs could help achieve.

Policy-relevant advances in N_2O research

The policy-relevant advances in N_2O research can be compiled into four categories: emission factors, modeling, mitigation measures and assessments.

Emission factors

Emission factors (EFs) can indirectly estimate greenhouse gas emissions from a range of production and consumption data, usually at national or international scales. The resulting emissions data are part of national GHG inventories, which provide the basis for reporting and communication of emission reductions to the UNFCCC. In the case of agricultural N_2O emissions, annual synthetic fertilizer and manure production and consumption data are multiplied by an EF to estimate annual emission fluxes. The most widely used EFs for N_2O were developed by the Intergovernmental Panel on Climate Change (IPCC) and assume a linear relationship between N application rates and N_2O emissions [12]. For example, a 1% EF is applied to synthetic N fertilizer rates to estimate direct emissions (i.e. for every 100 kg N applied, 1 kg of N_2O is emitted). However, recent studies are finding nonlinear relationships, implying that N_2O emissions per hectare are lower than the IPCC EFs at low N application rates, and higher at high N application rates – likely driven by excess N not taken up by crops, which can then be emitted as N_2O [13]. For example, applying the IPCC Tier 1 EF to a 50 kg N ha^{-1} reduction in N application rate would generate an estimated reduction in N_2O emissions of 0.5 kg N_2O-N ha^{-1}, regardless of the initial application rate. However, using a nonlinear EF for upland grain crops derived via meta-analysis, a reduction from 50 kg N ha^{-1} to zero would reduce emissions by 0.37 kg N_2O-N ha^{-1}, while a reduction from 300 kg N ha^{-1} to 250 kg N ha^{-1} would reduce emissions by 0.84 kg N_2O-N ha^{-1}, suggesting greater mitigation potential in regions with higher N application rates [14]. This not only has implications for how agricultural N_2O emissions are estimated in national and regional inventories, it also suggests that in regions of the world where many farms apply N at very low rates, such as sub-Saharan Africa and parts of Eastern Europe, increases in N fertilizer use would generate relatively small increases in agricultural N_2O emissions depending on the agronomic practices and associated N use efficiency of the crops [15]. Similarly, even moderate decreases in highly fertilized regions could trigger significant emissions reductions. Nevertheless, it should be noted that addressing the effect of N application rates to soils on N_2O emissions remains challenging because most countries do not have census or survey data on this metric, particularly in developing countries. Instead, the national total N added to soils is often the only available information.

Another recent advance in EF development regards indirect emissions – N_2O formed from other N compounds lost to the environment, namely nitrate (NO_3^-), nitrogen oxides (NO_x) and ammonia (NH_3). Recent studies suggest that IPCC EFs for indirect emissions are low, especially the 0.75% EF for indirect N_2O from leached NO_3^-. One study in the U.S. Corn Belt estimates an EF closer to *2%* which could translate to an underestimation of total agricultural N_2O emissions in the region of up to 40% [16]. In fact, the IPCC has recently raised the global default value to 1.6% for synthetic fertilizer application in wet climates [17•], implying greater emissions than previously considered and even larger mitigation potentials. However, the IPCC also lowered the default value for drier climates to 0.5%, suggesting lower emissions and likely less mitigation potential in semi-arid and arid regions. Finally, several countries have now developed country-specific emission factors. This is particularly important in capturing national climatic, agronomic and other conditions [18,19].

Modeling

A major recent development in N_2O modeling is the combination of a multi-inversion approach with an ensemble of surface observations to better constrain the regional and temporal distribution of N_2O emissions. Recent estimates suggest total global N_2O emissions of 15.3–17.3 (bottom-up) and 15.9–17.7 Tg N (top-down), demonstrating relatively close agreement [4,20]. Inversion approaches have also enabled more accurate regional quantification of N_2O emissions, showing good agreement between European inventories and measurements [21,22] while highlighting underestimates for North

American inventories [23,24]. A recent global intercomparison of inverse models confirms the utility of N_2O emission factors as well as the continental-scale non-linear relationship between N application and N_2O response noted in Section “Emission factors” [25].

More detailed terrestrial biosphere models are able to generate high resolution estimates of land-based N_2O emissions from anthropogenic and natural sources [26]. In addition, advances in soil process modelling have led to more detailed representations of nitrification and denitrification, the biogeochemical processes underpinning soil N_2O emissions, across multiple temporal and spatial scales. For example, the United States has reduced uncertainty in national estimates of agricultural soil N_2O emissions from +184%/−70% using IPCC default emission factors to +49%/−33% by applying process-based models [27]. Such models have been able to integrate effects like freeze-thaw cycles [28,29] – the omission of which could lead to an underestimation of global agricultural N_2O emissions by 17 %–28% [30] – and non-linear N_2O emission responses to N input applications [31]. Several integrated assessment models – models combining biophysical and economic components – and crop models have been used to quantify agricultural N_2O emissions from plot to global scales [32]. However, bottom-up inventories for most non-agricultural sector-specific emissions are still based on IPCC EFs due to limited development of more advanced methods for these sources [33].

Modeling has also contributed towards a better understanding of how future changes in climate could impact N_2O emissions. Warmer and wetter conditions will enhance the conditions for soil N_2O emissions, acting as a positive feedback to climate change [34••]. Indeed, changes in precipitation alone are projected to increase total N loading to rivers by 19% within the continental United States by the end of this century, with important implications for indirect N_2O emissions. Offsetting this increase would require a 33% reduction in N application rates [35]. Climate change is also expected to cause changes in land use and management, which will likely impact terrestrial biogeochemical cycles. An increase in the area of irrigated agricultural land could stimulate N_2O emissions increases of 50%–150%, likely a result of increased denitrification activity [36,37]. Studies focused on N cycling and CO_2 fertilization estimate that the cumulative warming effect of methane (CH_4) and N_2O emissions over the period 2001–2010 was a factor of two larger than the cooling effect that resulted from CO_2 fertilization [38••], suggesting that mitigation efforts should be as focused on reducing emissions of these non-CO_2 greenhouse gases as on increasing carbon storage capacity. Finally, a number of different emissions scenarios for N_2O over the 21st century have provided policymakers and other stakeholders insight into the risks of no action and the potential benefits of ambitious mitigation [5].

Mitigation measures

N_2O mitigation technologies and practices exist across all sectors. Technologies in non-agricultural sectors such as transport, energy, and industry (nitric and adipic production) are already well established and widely used, particularly in OECD countries, with mitigation potentials greater than 80% [5,39,40••]. For example, the EU Emissions Trading System has already spurred the wide-scale adoption of N_2O abatement technologies in nitric acid plants. The agricultural sector has traditionally lagged behind given its heterogeneity, high mitigation costs, more modest mitigation potential compared to other sectors, and a powerful political lobby [40••,41]. For example, a recent analysis of US cropland estimates that a carbon price of 35 USD per tonne CO_2 equivalent, which is relatively high compared to current market prices, would reduce N_2O emissions by less than 4% [42].

And yet, recent studies suggest how the N_2O mitigation potential of the agricultural sector can be unlocked. A number of meta-analyses evaluating enhanced efficiency fertilizers (EEFs, which include nitrification and urease inhibitors as well as controlled-release fertilizers) have found them to reduce field-level N_2O emissions by up to 50%, while boosting yields and N use efficiency (NUE) [7]. Other mitigation options based on changes in farm practices and the adoption of precision agriculture technologies, such as applying fertilizers at optimal rates, have the potential to reduce field-level N_2O emissions by up to 40% [5,40••]. Furthermore, several disruptive technologies could fundamentally transform how humanity contributes to the N cycle, including the development of ‘meatless’ meat and N-fixing cereals [43,44]. If widely adopted, these technologies could lead to significant reductions in N_2O emissions [45]. However, there is still much progress to be made in developing technologies uniquely adapted to specific climates, crops and cultures. Governments could therefore play an important role in technology development, akin to what the U.S., government has done to spur the development of more environmentally friendly cars via fuel efficiency standards [7]. This could be particularly impactful in the fertilizer sector, given the conservative R&D culture that currently prevails. Indeed, one of the most important ripple effects of the Paris Climate Agreement has been the signal sent to the marketplace that the international community is committed to addressing climate change [46].

Assessments

Since 2011, four major N assessments have been released in Europe [47••], the U.S. [48], California [49] and India [50], with the first international N assessment scheduled for release in 2022 under the auspices of the International Nitrogen Initiative (INI) and the International Nitrogen Management System (http://www.inms.international). These assessments differ from IPCC reports given their singular focus on N while providing an in-depth examination of its particular region's N budget, impacts, mitigation opportunities, future scenarios and policies. From a policy perspective, the European N assessment excelled in being one of the first to estimate damage costs for each major N compound [51], including N_2O, spurring a burgeoning literature on this topic [52,53]. For example, a recent cost–benefit analysis evaluating N_2O mitigation options in the United States demonstrated that by 2030 if only the climate and stratospheric ozone benefits from avoided N_2O emissions are evaluated (estimated to be approximately $1.8 billion), the cost of action (approximately $22 billion) would be prohibitively expensive. However, if the total avoided N pollution is considered, then the benefits (approximately $91 billion) would outweigh the costs by a ratio of over 4:1 [54]. In addition to this new economic framing, the U.S. assessment recommended a range of specific management strategies, and the California assessment took this a step further by developing a policy evaluation framework uniquely suited to N [55,48].

These assessments are not only an important informational resource to policymakers; they perform an important political role by communicating a clear scientific consensus that can provide a basis and momentum for policy development [56]. Looking ahead, the International Nitrogen Assessment will need to be genuinely multi-disciplinary, integrating social sciences into the framing and development of the report in order to address the N issue in a way that is relevant to policymaker concerns – examining the obstacles to better N management and a broader policy approach across the entire agri-food chain. This in turn would likely raise N_2O's profile in ozone and climate negotiations.

Implications for climate policy

Taken together, the scientific advances in emission factors, modeling, mitigation technologies and assessments mean that the next round of NDCs, as well as other future policy efforts to limit greenhouse gas emissions, could include targets specifically focused on N_2O. This could help many countries, particularly ones with large agricultural sectors, develop mitigation pathways consistent with a 2°C, and possibly a 1.5°C world [57]. For example, countries with high agricultural N surpluses like China could significantly reduce application rates and thus N_2O emissions with little to no yield penalty [58]. In another example, Uruguay's food sector is responsible for close to three quarters of their national GHG emissions, with N_2O contributing one third of national emissions. Consequently, its first NDC set an economy-wide target of reducing N_2O emissions intensity by 51%–57% below 1990 levels by 2030, and 37%–43% in the livestock sector. These targets are based on a technical evaluation of different mitigation measures, which include the implementation of nutrient recovery technologies on at least 40% of dairy farms and the adoption of regenerative management and other N management techniques on 10% of grasslands [59]. Other approaches could adopt cost-benefit analysis, backcasting (working back from a set target based on technical analysis and stakeholder consultation to develop a pathway for achieving it) and/or optimization tools such as the GAINS model [40••,60]. Even if agriculture is not an especially important contributor to a country's total GHG emissions, targets for non-agricultural N_2O emissions could be developed based on the technical and economic information available for mitigation strategies in the industry, energy, waste and transport sectors. N_2O-specific national targets would enable more transparent comparisons of NDCs, and thus make it easier to independently track their progress and potentially incentivize increased ambition over time.

Finally, while it is understandable that countries may wish to maintain a basket approach and not set GHG-specific targets in order to maintain flexibility, the case for N_2O targets goes beyond the climate benefits, as noted above. If implemented properly with a view towards the N cascade, N_2O mitigation could deliver local environmental benefits whose economic value could vastly outweigh the climate benefits – a particularly important characteristic given the current political climate of economic nationalism across many major countries [6•]. Furthermore, given the extensive links between N and the Sustainable Development Goals – a set of social, economic and environmental targets adopted by the United Nations in 2015 – better N management associated with N_2O mitigation could help achieve several of the 17 targets, from more responsible production and consumption to protecting life on land and in water [61].

Conclusion

Science and technology have advanced to a point that policymakers could include specific N_2O mitigation strategies in future climate policies. Emissions can be estimated relatively accurately, particularly at national scales, and targets can be developed and implemented cost-effectively based on tried-and-tested technologies especially if the local co-benefits of mitigation are taken into account. Furthermore, the relationship between policy and science and technology is a two-way street: a strong signal from the policy community that it is committed to acting on N_2O could stimulate more financial and intellectual resources being allocated to this issue, and thus potentially accelerate the development and deployment of N_2O mitigation options. This would be true not just for the scientific community, largely funded by public research programs, but also the R&D investments of the private sector, whose technologies could be further tailored to specific crops, climates and cultures. Ultimately, humanity has an extremely small window in which to stay below a 2°C global average temperature increase. More focused action on N_2O could help meet these targets while achieving a range of other goals from biodiversity protection to improved air and water quality.

Conflict of interest statement

Nothing declared.

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