SCIENTIFIC PANEL
ON RESPONSIBLE PLANT NUTRITION

MITIGATING GREENHOUSE GAS EMISSIONS THROUGH RESPONSIBLE PLANT NUTRITION

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KEY POINTS

The provision of nutrients for crop growth in the form of inorganic or organic fertilizers results in greenhouse gas (GHG) emissions from the processes involved in their manufacture and delivery to the farm as well as from the soil after application. Opportunities exist for reducing emissions along the whole fertilizer supply chain. At issue is how to achieve emission reductions at large scales in balance with the need to secure food production and farmers' incomes. Reducing soil GHG emissions in the form of nitrous oxide (N_2O) and improving fertilizer nitrogen use efficiency (NUE) are of particular importance.

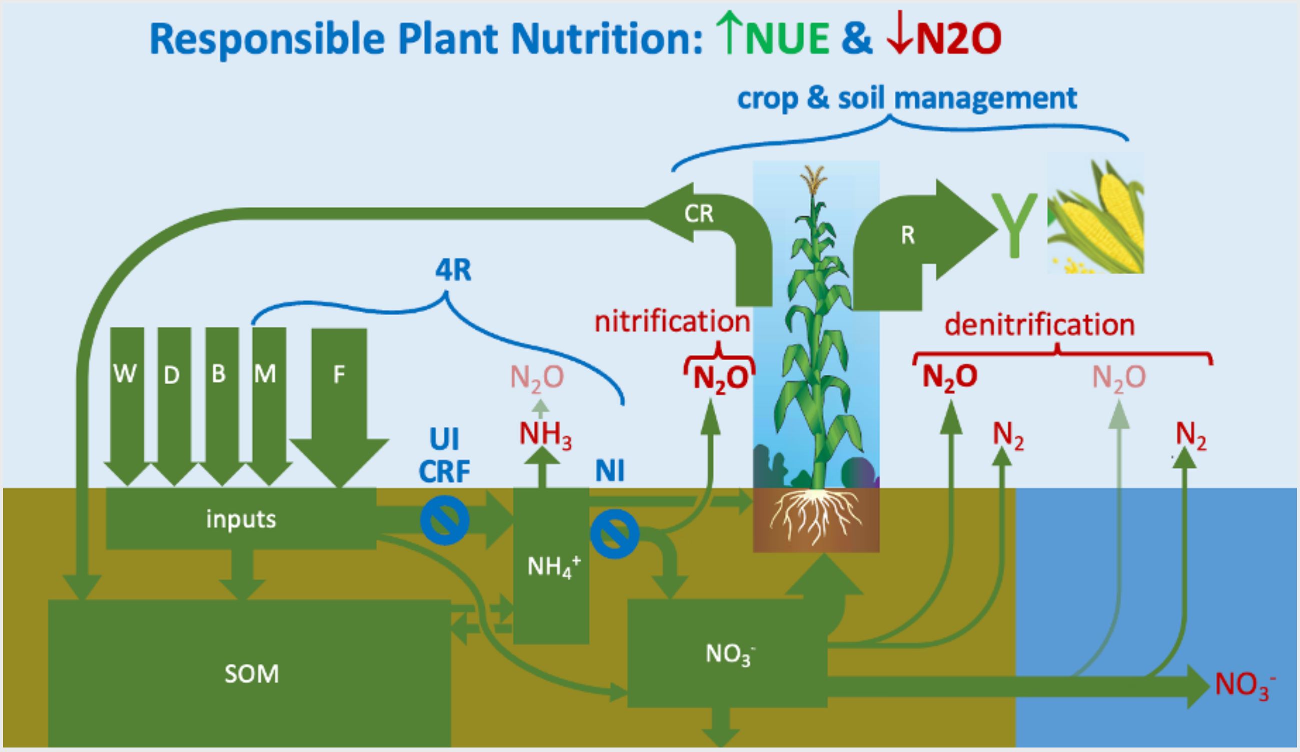

Figure 1. Sources of nitrous oxide (N_2O) emissions arising from nitrogen (N) inputs to agricultural soils. Emissions increase when fertilizers (F) or manures (M) are applied. Direct emissions occur when ammonium (NH_4^+) is nitrified, and when nitrate (NO_3^-) is denitrified. Indirect emissions arise from losses to drainage water and from ammonia (NH_3) losses to air. Additional inputs include biological nitrogen fixation (B), atmospheric deposition (D), and irrigation water (W). The return of crop residues (CR) also contributes N to the soil pools from which N_2O is emitted. Optimizing N use efficiency (NUE)—by matching inputs to crop removal (R) as closely as possible—is achieved through management of inputs (4R), crops and soils to optimize yields (Y). Improvements in NUE reduce fertilizer emissions per unit of crop produced. Nitrification inhibitors (NI), controlled release fertilizers (CRF), and urease inhibitors (UI) are effective 4R practices that decrease N_2O emissions per unit of N applied.

Emissions of N_2O from the soil are highly variable, driven by soil and climatic factors as well as the interaction of those factors with management practices. Despite this variability a range of interventions under the framework of responsible plant nutrition have been shown to reduce emissions. These interventions include both 4R nutrient stewardship practices and crop and soil management practices that enhance crop yields and crop nitrogen removal. The 4R source practices that inhibit nitrogen transformations can directly reduce field emissions of N_2O, while all 4R components (source, rate, time, and place) along with crop and soil management can improve NUE, with impact on all emissions from the whole fertilizer supply chain. These practices have potential to mitigate a large fraction of annual emissions of GHG from fertilizer use within the next few decades, particularly when applied in combination.

We suggest actions that would prioritize the most appropriate mechanisms in target regions to ensure short-term success while also allowing for long-term progress. Social and economic constraints affecting farmer capacity to adopt emission-mitigating practices need to be addressed to achieve broader impact. New emission inventory methodologies and market-driven credit schemes need to be created to support solutions that lead to proven reductions in GHG emissions arising from fertilizer use.

WHAT ARE THE ISSUES?

Urgent action is required across all sectors of human activity to reduce GHG emissions and mitigate the impact of climate change, including the agrifood sector *(1)*. In 2021, emissions from the entire agri-food sector were about 16 billion tonnes of carbon dioxide equivalent (Gt CO_2e), or about 30% of total anthropogenic emissions (53 Gt CO_2e) *(2)*. Agri-food emissions were largest in Asia (6.8 Gt CO_2e) and the Americas (4.3 Gt CO_2e), reflecting the large sizes of their populations and geographical areas. On-farm operations involved in producing food and other outputs (i.e. farm-gate) contributed 48% of all agrifood systems emissions, while pre- (e.g. fertilizer production) and post-production (e.g. food packaging) processes contribute about 33% and land-use change 19% (Fig. 2). Due to increased agricultural productivity and efficiency, the per capita emission of GHG for food production has actually decreased over time. In 1990, the average person's food-related emissions amounted to 3.0 t CO_2e/yr, but that number decreased to 2.4 t CO_2e/yr by 2015 *(3)* and about 2 t CO_2e/yr in 2021 per capita *(2)*.

The agrifood sector plays an important role in meeting global emission reduction targets *(4)*, while it also has to ensure food security and soil health, preserve biodiversity, reduce environmental impacts, and improve farmers' incomes. Increasing crop yields and nutrient use efficiency on the existing agricultural land through responsible plant nutrition will be critical for achieving these goals *(5)*. Providing nutrients in the form of mineral fertilizers to support crop growth results in GHG emissions associated with activities such as extraction, production, and processing. Emissions also arise from the transport and utilization at the farm level, i.e. from machinery used and from soils, the latter induced by application of N fertilizers *(6)*.

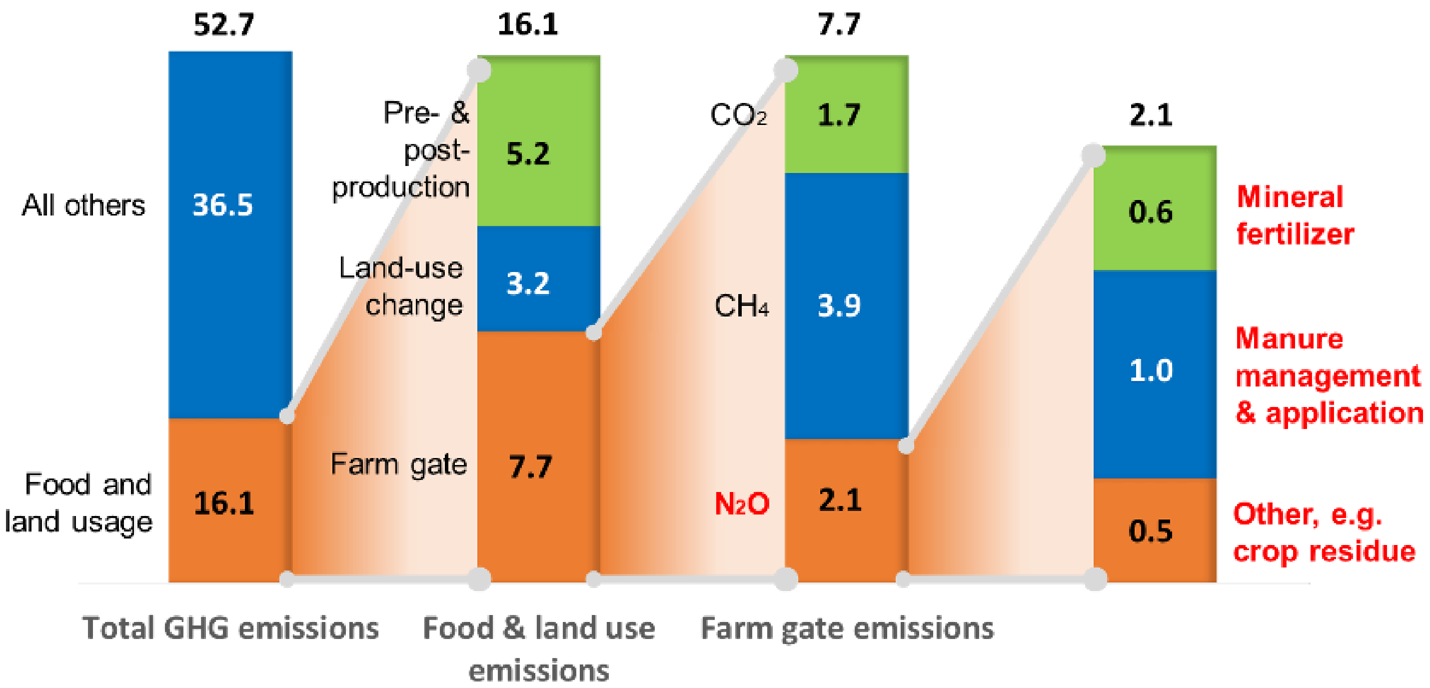

Figure 2. *Annual greenhouse gas (GHG) emissions (Gt CO_2e) of the agri-food sector by greenhouse gases and primary sources. Values shown are averages of 2017-2021. Values at the top of each bar are the sum of each component shown. The right-most column provides a breakdown of farm-gate N_2O emissions. GHG emissions associated with production and transport of fertilizer (not shown) amount to ~0.5 of the 5.2 Gt CO_2e shown for pre- & post-production. Source: FAOSTAT Emission totals, https://www.fao.org/faostat/en/#data/GT.*

Nitrogen is the essential plant nutrient with the largest GHG impact. Table 1 summarizes the global GHG emissions associated with the production and use of N fertilizers in 2018, adapted from a study which considered multiple sources of information, including the Intergovernmental Panel on Climate Change (IPCC) and Food and Agricultural Organization(FAO) *(7)*. Firstly, the energy-intensive process of synthetic N production is estimated to be responsible for 0.44 Gt or 440 Mt CO_2e/yr. Secondly, N fertilizer input to soil increases microbial production of the powerful GHG nitrous oxide (N_2O), termed direct N_2O emissions; N losses in the form of ammonia volatilization and nitrate leaching further result in N_2O emissions off-site, termed indirect N_2O emissions (Fig. 1). Thus, the direct and indirect field emissions of N_2O contributed 0.6 Gt CO_2e of 52.7 Gt CO_2e global emissions (Fig. 2) or 0.66 Gt CO_2e if CO_2 release from urea is included (Table 1). Summing the production, transport, and in-field emissions, the synthetic N fertilizer supply chain contributed 1.13 Gt CO_2e, or 2.1% of all global GHG emissions (Table 1). China, India, USA, and EU28 accounted for 62% of the total fertilizer N emissions. It should be noted, however, that these estimates have an average uncertainty of about ±15%, mostly due to uncertainties of direct and indirect N_2O field emissions (±42 and ±24%, respectively) *(7)*.

1. CO_2e – CO_2 equivalent as measure to account for the different global warming potential of CO_2, N_2O, and CH_4
2. Commonly included in Scope 1 and 2 emissions for the fertilizer industry
3. Commonly included in Scope 3 emissions for the fertilizer industry

Table 1. Estimated global greenhouse gas emissions from production and use of inorganic N fertilizers in agriculture in 2018 *(7)*. Note that the sum of indirect and direct N_2O emissions equals 662 Mt CO_2e (=0.662 Gt CO_2e while values in Fig. 2 show 0.6 Gt CO_2e due to the differences in the time period).

FERTILIZER SUPPLY CHAIN GHG EMISSION COMPONENTS	Mt* CO_2E	SHARE (%)
Synthetic N production	439	38.8
Transport	30	2.7
Direct field emissions (N_2O, CO_2)	466**	41.2
Indirect N_2O emissions	196***	17.3
TOTAL EMISSIONS	**1131**	**100**

* million tons (1 Mt = 0.001 Gt)
** 380 Mt CO_2e as direct soil N_2O emissions plus 86 Mt CO_{2e} as CO_2 liberated from urea fertilizer
*** 66 Mt CO_2e as indirect N_2O derived from ammonia volatilization and redeposition and 130 Mt CO_2e as indirect N_2O derived from nitrate leaching

Emissions of N_2O from manure management and application of other organic fertilizers add another 1.0 Gt CO_2e annually (Fig. 2). Summing the above, direct and indirect N_2O emissions associated with use of mineral N and organic fertilizers are in the order of about 2.13 Gt CO_2e annually, or roughly 4% of the world's total emissions, representing a significant mitigation potential (Fig. 2). Producing and using other mineral fertilizers, such as phosphorus (P), or potassium (K), create additional GHG emissions that are not included here, but these have been estimated to be very small compared to N related emissions (e.g. 0.04 Gt CO2e for China in 2020 *(8)*).

While the use of N fertilizers contributes to GHG production, the efficient use of plant nutrients in agriculture can also play an important role in the mitigation of GHG emissions by: 1) enabling crop production intensification on existing land, thus avoiding deforestation and land clearing which are the major causes of CO_2 emissions from land (see land-use change in Fig. 2); 2) supporting the growth of biofuel crops as renewable energy sources; and 3) supporting growth and removal of atmospheric CO_2 by plants that can lead to build up of soil organic matter *(9)*. Hence, opportunities to mitigate agri-food system GHG production include sustainably increasing crop yields, recycling more nutrients and increasing N use efficiency (NUE) on existing land, in addition to other actions such as prioritizing crop production for human consumption, changing diets, reducing food waste, and decarbonizing supply chains *(10, 11)*. Importantly, increasing NUE and minimizing direct and indirect emissions of N_2O present the most relevant opportunities for reducing emissions associated with fertilizers *(6)*.

At issue is how to balance the need for using N fertilizers to support food production with the quest for reducing climate impacts of N fertilizer use, specifically by reducing direct and indirect N_2O emissions. In this issue paper, we focus on the specific role of responsible plant nutrition to mitigate these GHG emissions. We discuss practices and technologies that mitigate GHG emissions related to N fertilizer use, and identify challenges to the implementation of solutions and the quantification of emission reductions. Finally, we suggest how various stakeholders can contribute to addressing these challenges.

WHAT IS HAPPENING?

GLOBAL NITROGEN FERTILIZER RELATED TRENDS

The general global trajectory from the 1960s to 1990s has been an increase in N fertilizer use and crop production (N yield) accompanied by increasing N surplus and a decline or stagnation of cropland NUE *(12)*. In the most recent decades, global crop production and N input (including fertilizer, manure, biological N fixation, seed, and atmospheric deposition) continued to rise. At the same time, global NUE increased to about 55% in 2021 (Fig. 3). The annual N surplus has remained fairly steady at about 80 million tons of N, although huge regional differences exist *(3, 12)*. During this period, farm gate N_2O emissions have risen to 2.1 Gt CO_2e by 2021 (Fig. 3), mostly associated with mineral and organic fertilizer use (Fig. 2). The key challenge is to shift these trends towards more significant reductions of N surplus and N_2O emissions – while continuing to increase productivity and NUE. The decrease in the ratio of N_2O emission to N input apparent in Fig. 3 arises from an increase in the proportion of total N input from biological fixation, accompanied by a decrease in the proportion from manure.

CHARACTERISTICS OF NITROUS OXIDE EMISSIONS

Nitrous oxide emission from soils primarily results from microbial nitrification and denitrification processes. These are regulated by numerous environmental conditions and specific abiotic processes *(13)*. For example, after N fertilizer application and heavy rainfall events, a surplus of inorganic N and/or moisture in the soil enhances N_2O emissions. Conditions that drive N_2O-producing microbial processes in soils are highly variable in space and time, resulting in emissions that are characterized as occurring in 'hot spots' and at 'hot moments', with a large percentage of emissions originating from brief, unpredictable events or from small areas in a field *(14)*. The magnitude of these emission events is impacted by soil and climatic factors and their interactions with soil and crop management practices. The emission characteristics of soil N_2O present challenges for measurement as well as identification and implementation of mitigation practices, which are generally regarded as being soil-, crop-, and climate-specific.

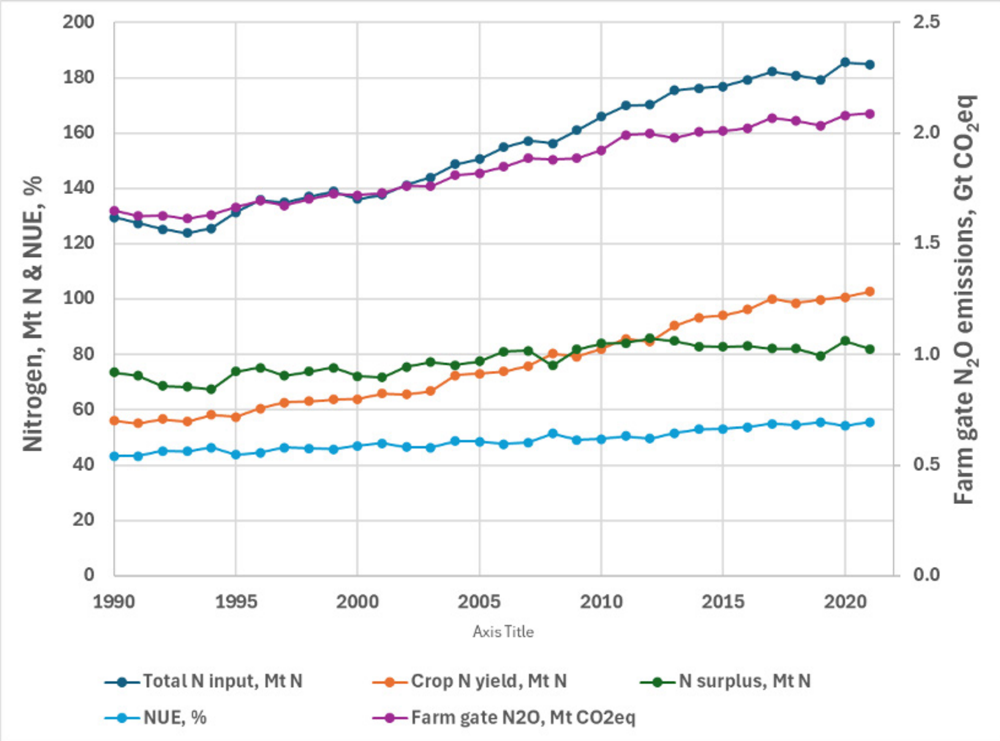

Figure 3. Changes in global cropland nitrogen (N) input, crop N yield, N surplus, nitrogen use efficiency (NUE) and farm gate nitrous oxide (N_2O) emissions from 1990 to 2021. Source: and FAOSTAT Emissions totals.

INTERVENTIONS TO REDUCE N_2O EMISSIONS

A range of interventions have been shown to reduce soil N_2O emissions, including the use of novel fertilizer products and improved agronomic practices (Fig. 1) *(15)*. These interventions in combination with soil carbon gains from improved productivity with balanced plant nutrition practices hold great promise as a means to reduce GHG emissions from agriculture *(16)*. However trade-offs need to be considered as increasing soil organic carbon and hence soil fertility can increase N_2O emissions, potentially offsetting climate change benefits from increased carbon sequestration *(17)*. Nitrogen fertilizer additions need to be adjusted accordingly. Reducing N_2O emissions is a permanent benefit in contrast to soil carbon gains which can be reversed with soil carbon release through subsequent agricultural practices such as increased tillage.

Effective interventions for soil N_2O emission reduction are captured under the 4R Nutrient Stewardship framework which is focused on the 4 “rights” (source, rate, time, and place) of nutrient applications. The New Paradigm for Responsible Plant Nutrition has broadened the scope of relevant practices and added to the 4R principles consideration of climate-smart fertilizers, i.e., using fertilizer sources with reduced carbon footprint, including emissions associated with both manufacture and use (18). Although users of the 4R framework often focus on mineral fertilizer use, its integration with organic fertilizer management is extremely important. For example, recycling organic N sources such as manure avoids GHG emissions associated with production of N fertilizer, while adjusting fertilizer N rate to account for N supplied by organic sources contributes to soil N_2O emission reductions. The 4R practices discussed here need to be considered in a wider context of N management, including organic sources. A summary of the reductions in soil N_2O emissions and changes in crop yield for various 4R and crop management practices is presented in Table 2. Owing to the high variability associated with N_2O emissions, ‘summary effects’ of practices are typically derived from meta-analyses applied to multiple site-years of research across a wide range of conditions.

ENHANCED EFFICIENCY NITROGEN FERTILIZERS

Most meta-analyses confirm a strong effect of ‘enhanced-efficiency fertilizers’ (EEFs, including nitrification inhibitors, urease inhibitors and/or controlled-release fertilizers) on N_2O emissions (Table 2). Consistent emission reductions are seen for these EEFs (36% across 608 peer-reviewed studies worldwide *(19)*, but individual meta-analyses show a range of values for the different EEF types, with highest reductions generally observed from use of nitrification inhibitors (Table 2). In vegetable crops, controlled release fertilizers reduced N_2O emissions on average by 24%, whereas nitrification inhibitors reduced them by 40%, with both technologies increasing yield by about 8% (20). Fertilizer sources can also affect N_2O emissions in different ways. For example, in regions such as Ireland, which have mild, wet climates and high organic matter soils, significant reductions in N_2O emissions were achieved by switching from nitrate-based fertilizers to urea with added urease or nitrification inhibitors *(21)*. On the other hand, in a field experiment with drip-fertigated crops in Spain, lower emissions were measured from calcium nitrate as compared to urea *(22)*.

In summary: (i) reductions in N_2O emissions due to EEFs are generally larger than their positive effects on crop yield or NUE *(23)*; (ii) nitrification inhibitors are most effective in reducing N_2O emissions, but may also increase ammonia volatilization losses; and (iii) in many situations combining urease and nitrification inhibitors can be recommended to avoid pollution swapping. For example, in the case of using a urease inhibitor alone, direct N_2O emissions may increase even though indirect N_2O emissions may be reduced *(24, 25)*. In addition to impacts on GHG emissions, EEFs generally also reduce nitrate leaching losses from the soil by about 20-40% *(26)*. This decrease in N loss provides additional environmental and economic benefits, through reduced indirect N_2O emissions, reduced contamination of groundwater, and reduced fertilizer costs.

Table 2. Relative changes (%) in N_2O and NH_3 emissions and crop yield due to 4R and crop management practices. Sources: Meta-analyses summarizing the global literature.

PRACTICE	N_2O EMISSION %	NH_3 EMISSION %	CROP YIELD %	N* (FOR N_2O)	SOURCE
Crop rotation	-4		-2	1	*(19)*
Cover cropping	-5		+12	3	*(19)*
Fertilizer rate	-9	-31	-4	7	*(19)*
Fertilizer timing	0	-32	+4	3	*(19)*
Fertilizer placement	-15	-43	-5	1	*(19)*
Fertilizer source:					
Nitrification inhibitor	-50	+20	+2	422	*(27)*
Urease + nitrification inhibitor	-30	-38	+3	118	*(27)*
Urease inhibitor	-10	-50	+6	116	*(27)*
Controlled-release fertilizer	-19 to -33	-65	-3	276	*(28-30)*
Maize EEF**	-25		+4	429	*(30-31)*
Wheat EEF**	-29		+5	279	*(30-31)*
Rice EEF**	-25		+8	312	*(30-31)*

*N represents number of meta-analyses for source *(19)* and number of site-years for the rest
**EEF:enhanced-efficiency fertilizers that included nitrification/urease inhibitors and slow-release fertilizers

FERTILIZER TIMING AND PLACEMENT

The effects of timing and placement of N fertilizers are usually smaller and less consistent than those of EEF (Table 2). Young et al. *(19)*, in a synthesis of 113 meta-analysis studies, reported that optimal fertilizer placement decreased direct N_2O emissions by 15% and NH_3 emissions by 43% (which would reduce indirect N_2O emissions), and increased yield by 5%. Optimal timing had no significant effect on direct N_2O emissions, while on average it reduced NH_3 emissions by 32% (Table 2).

BIOLOGICAL NITRIFICATION INHIBITORS

While the studies on inhibitors summarized in Table 2 refer only to manufactured inhibitors added to inorganic fertilizers, there also exists the potential to modify biological nitrification based on compounds exuded by plants that may suppress nitrification and N_2O emission. A recent survey of the literature found that "Primary metabolites, such as sugars, amino acids, and organic acids, strongly stimulated soil N_2O emissions, by an average of 79%, while secondary metabolites, such as phenolics, terpenoids, and flavonoids, often characterized as both biological nitrification inhibitors (BNIs) and biological denitrification inhibitors (BDIs), reduced soil N_2O emissions by an average of 41%." *(32)*. Biological nitrification inhibition explains, for example, the low N_2O emission rates observed from Brachiaria, a grass species often used as pasture and cover crop in Brazil. Some potential may exist to strengthen BNI traits in high-yielding cereal crops through plant breeding *(33, 34)*. However, feasibility and efficacy of BNI compared to synthetic nitrification inhibitors has not been fully explored.

NITROGEN RATE

The rate of N fertilizer applied has been widely used in GHG accounting to estimate N_2O emissions. The IPCC established an average fertilizer-induced direct emission factor (EF) of 1% (uncertainty range: 0.1-1.8%) for global estimates; that is, for every 100 kg N applied, 1 kg of N_2O-N is emitted directly from soils *(35)*. The IPCC provides some further differentiation, e.g. a 1.6% EF for fertilizer used in 'wet' climates, or an EF of only 0.3% in continuously flooded rice fields. Although the IPCC value has proven robust for N_2O emission estimates for regions that lack locally derived EFs, research has shown that EFs can vary widely and, in many cases, are also significantly lower than 1%. In Australia, for example, the average EF of mineral N fertilizer was 0.70%, with a range of 0.17-1.77% across regions and cropping systems *(36)*. In Germany, the district-wise EFs ranged from 0.38% to 0.92%, with a national average of 0.62% *(37)*. In a global spatial analysis, average estimated EFs were 1.02% for maize, 0.58% for wheat, and 0.52% for rice, but varied widely, including hotspots with higher values (38). Similarly, Wang et al. *(39)* generated global maps of EFs with an average of 0.88% for maize and 0.65% for wheat. Yao et al. *(31)* found average global EFs of 0.69% for maize, 0.60% for wheat, and 0.36% for rice.

On the other hand, the global agri-food system also includes production systems in which N application rates, N_2O emissions, and EFs are particularly large. For example, although tea plantations account for only 0.3% of total cropland area, they have been estimated to account for 1.5%–12.7% of total direct cropland N_2O emissions, with average losses of 17 kg N ha-1 in the form of N_2O emissions and a global mean EF of 2.3% *(40)*. These high EFs are driven by N application rates that far exceed the tea crop N demand, inducing an exponential increase in soil N_2O emissions with rates exceeding 250kg N/ha/yr. Such global hotspots must be addressed with particular urgency.

The general assumption in using EFs is that the N_2O emission rate is a linear function of N rate, an assumption that is likely incorrect.

Shcherbak et al. *(41)* reviewed 233 site-years of studies with at least three N levels and found that N_2O emissions responded non-linearly to N rate, demonstrating that reducing N that is in surplus of crop needs would be most effective in reducing emissions. The principles of plant nutrition suggest that at the optimal N rate for a crop grown in a specific environment, NUE is high, N surplus is low, and N losses and N_2O emissions are also likely to be lower than at rates exceeding the optimum. This principle has been implemented, for example, in the N balance model of the Environmental Defence Fund *(42, 43)*. The key implication is that regions where N is applied in excess of optimal fertilizer rates have the largest N_2O mitigation potential arising from rate reduction.

INTERVENTIONS TO INCREASE YIELDS AND N USE EFFICIENCY

In regions with low N use or nutrient deficiency there is little potential to mitigate current N_2O emissions, but the need to increase yields on existing cropland to improve food security and avoid the CO_2 emissions that arise from deforestation and land clearing must be recognized. These regions are particularly common in sub-Saharan Africa. Many of these regions feature soils that have been degraded and require both mineral fertilizers and organic inputs, along with sound agronomic practices, superior seed varieties, soil amendments, and other measures, as prescribed by the principles of Integrated Soil Fertility Management, or ISFM *(44)*. There are also opportunities to sequester carbon in these soils *(45, 46)*, but such carbon first needs to be produced through increased crop yields. The assessment of the full net impacts on GHG emissions, land-use change, and soil carbon sequestration arising from the wide array of site-specific ISFM practices is beyond the scope of this paper. It should nevertheless be recognized that the simultaneous improvements achieved in yields and N use efficiency in North America or other regions depended in large part on massive investments in crop genetic improvement as well as soil, crop and nutrient management *(47, 48)*. Similar investments will likely be required for other parts of the world where crop yields are far below potential, particularly in Sub-Saharan Africa *(49)*.

SUMMARY

A wide range of agronomic practices and 4R N management solutions have been shown to increase NUE and/or directly reduce N_2O emissions across regions and crops. These effective actions have potential to mitigate a large fraction of the 0.66 Gt CO_2e annual emissions of GHG from fertilizer use within the next few decades, particularly when applied in combination *(6, 39)*. These actions would make an important contribution towards achieving net-zero emissions by 2050 by reducing global agri-food system emissions (16 Gt CO_2e) *(4)*. Due to their large area and share of global N fertilizer consumption, grain production systems play a particularly important role in implementing GHG mitigation actions. At issue is how to achieve large-scale implementation of such measures.

WHAT CAN BE DONE?

RECOMMENDED IMPLEMENTATION ACTIONS

Identifying the most promising practices to reduce N_2O emissions is a necessary first step to achieve reduction targets but, ultimately, implementation is dependent on buy-in, trust, and actions from farmers. Depending on the region, practices that are 'win-win' may already be on their way to being adopted, or potential exists for adoption with appropriate knowledge and technology transfer programs. For other GHG reduction practices and technologies, incentives for farmers to adopt them could include reduced input costs, improved productivity, subsidized EEF products, payments, and sustainability-linked finance. Improved agronomic practices that boost crop productivity with the minimum amount of N fertilizer needed can incentivize farmers by helping them reduce input costs, while increasing income.

We group the potential solutions into three action targets, which are outlined in Table 4. Regions in which excessive N rates result in substantial N surplus should focus first on target 1 practices. Examples include many parts of China and India, but also some areas in Europe and North America with high cropping and livestock intensity *(50)*. In regions with substantial N surplus, the first priority would be to deploy the Right Rate principle, providing a win-win situation since GHG emissions would be reduced while profits would be increased. The achievable reductions could be significant. However, it is important that a non-linear EF model be used to capture decreases in N_2O emissions from reductions in N surplus as the linear EF model would underestimate potential emission reductions *(41)*.

Table 4. Overview of broad actions targetting N_2O emission reductions and their potential benefits

ACTION TARGET	PRACTICES	BENEFITS
1.Reduce excessive surplus nitrogen.	Right Rate, achieved through improved crop N demand prediction and improved manure management, and agronomic management to improve crop yield and N uptake.	Direct and indirect N_2O emissions are reduced; yield is not affected; NUE and profits are increased.
2. Reduce ammonia losses.	Right Time, Right Placement, and use of urease inhibitors or controlled-release fertilizers (Right Source) with adjustments in rate.	Indirect N_2O emissions are reduced; yield and NUE are increased; profits are potentially increased if rate is adjusted.
3. Reduce direct N_2O losses.	Use of nitrification inhibitors and controlled-release fertilizers (Right Source) with the Right Rate, Right Time and Right placement.	GHG emissions are reduced; yield and NUE are not affected or may increase slightly.

In regions where fertilizer N rates are already close to optimal (Right Rate), the focus should be on reducing N loss as ammonia through better timing, placement, and use of urease inhibitors or controlled-release fertilizers (Target 2; Table 4). Ammonia emissions can comprise a substantial fraction of the fertilizer N applied as urea. Reducing emissions would decrease indirect N_2O emissions and result in significantly increased yields, NUE, and profits. However, care must be taken to adjust the N rate to account for the ammonia reductions; otherwise, direct N_2O emissions can be increased due to higher N retention in the soil.

The third target would apply to situations where yields and N use efficiency are already close to optimal. Actions would prioritize direct N_2O emission reduction through practices such as using controlled-release fertilizers, nitrification inhibitors, or combinations of nitrification and urease inhibitors. Because N_2O emissions are small compared to N fertilizer input, nitrification inhibitors may not result in substantial yield increases and may not increase profits (Table 2). For that reason, support mechanisms may often be required to incentivize target 3 action. All three target practices could also reduce nitrate leaching, and thus have additional environmental benefits. It is likely that N loss in dinitrogen (N_2) form through denitrification would also be mitigated with target 3 actions, providing economic benefits, but there is little evidence for this given the difficulty in measuring N_2 gas emissions.

A combination of 4R practices is likely needed to achieve the largest GHG reductions. The proposed action categories in Table 4 are meant to be cumulative. For example, there may still be opportunity to adjust N fertilizer rates for areas that fall under targets 2 and 3 where rates are not excessive and close to the optimum due to uncertainty in crop N demand predictions. In these cases, farmers may still tend to use slightly more N fertilizer than needed to reach the economic optimum and additional incentives related to risk management may be required.

POLICIES TO DRIVE IMPLEMENTATION

The measures listed in Table 4 are potential means to improve NUE and reduce GHG emissions as well as other forms of N pollution, while meeting food security goals. Hence, redirecting public policy and subsidies towards their wide adoption should result in carefully designed regulations or incentives that are cost-effective, target hotspots, and consider the trade-offs among yield, profit, and environmental footprint *(51)*. Nitrogen use efficiency improvement targets can play a central role in achieving the right balance among the different goals to pursue. In China, for example, stricter environmental protection policies and improved N management led to a nationwide reduction in N fertilizer applied per area, increased NUE and slowed down growth in cropland N_2O emissions after 2003 *(52, 53)*.

Overall, however, evidence for successful policies that incentivize NUE increases, reductions in N pollution and N_2O emissions while also supporting food production remains quite scarce (54). For a long time, integrating N_2O mitigation into climate policy has received too little attention *(55)*. It should also be noted that further reductions in N loss in the long term will require profound food system changes, particularly shifts in diets in regions with high levels of food security *(56)*.

Incentives to adopt N_2O emission reduction measures can also come from carbon markets that would reward farmers financially for implementing practices to reduce emissions. Carbon credits in this case can be associated with any of the actions listed in Table 4, i.e. reducing the application rate of inorganic and organic fertilizers, increasing NUE, and/or directly reducing N_2O emissions through inhibitors or controlled-release fertilizers. Evidence-based methodologies (standards) must still be established for such purposes, including monitoring and verification. There is also growing interest in addressing Scope 3 GHG emissions by companies providing services or procuring products from the agricultural sector. Scope 3 emissions "are the result of activities from assets not owned or controlled by the reporting organization, but that the organization indirectly affects in its value chain" *(57)*. On-farm emissions such as soil N_2O emissions are significant Scope 3 emissions for companies selling N fertilizer or for companies purchasing agricultural products to be used within their supply chain. For example, a recent partnership between Nutrien Ag Solutions and Maple Leaf Foods for 4R Stewardship adoption by farmers in the Canadian Prairies is a value chain intervention addressing Scope 3 emissions by both companies. It aims to produce food products with lower carbon intensity by growing crops (e.g., canola, barley, wheat, peas) with optimized N fertilizer management *(58)*.

Sustainability finance may also incentivize low-emission practices. Governments, for example, may re-direct some of their financial support to farmers adopting NUE-increasing and emission-reducing practices. In other cases, banks may provide improved terms of finance, such as lower interest rates, as farm environmental performance improves. Such policy and market mechanisms may provide the needed incentives to tackle in particular target 3 type emission reduction practices (Table 4) which benefit the public more than the farmer.

METRICS TO MONITOR PROGRESS

Regardless of the mechanism used to incentivize action, metrics to monitor progress towards reduction or efficiency goals are needed. Sustainability metrics are an essential element of tracking the impact of improved N fertilizer management and to determine efforts by farmers, companies, or government in reducing their carbon footprints and meeting emission reduction targets. The availability of metrics also limits which practices are eligible for incentives. Existing GHG methodologies are mostly based on IPCC guidelines that only consider the N rate, but not other 4R practices such as placement or use of inhibitors. Hence, carbon reduction protocols often focus on reducing the N rate rather than increasing NUE, which may create undesirable yield losses too.

An exception is the Nitrous Oxide Emission Reduction Protocol (NERP) implemented in Alberta, Canada, which included 4R practices beyond N rate (59). The approach was adopted by several supply-chain initiatives which aim to quantify and monitor GHG emissions from organizations along the agricultural value chain. However, several gaps remain, including evaluating regionally specific management practices, assessing the 4Rs used as suites of practices rather than individually, evaluating variable-rate and source fertilizer technology, and quantifying the impact of single vs. dual use of urease and nitrification inhibitors. Furthermore, the interactions with other conservation practices, such as diversifying crop rotations or cover crops are not represented yet.

Additionally, a pragmatic approach could be to estimate N_2O emissions as a function of the partial crop N balance. As suggested by several studies, this would include the difference between N inputs (fertilizer, manure, other sources) and N removed by crop harvest *(15, 43, 60, 61)*. Emissions of N_2O have been found to relate as well or better to N balance than to the rate of N applied (15). Generalized relationships have been developed for multiple crops in North America *(43)* and globally *(15)*. These show that, in cereal cropping systems, N_2O emissions are likely to be higher once the N surplus exceeds about 50 kg N/ha. Using surplus reduction as an indicator of emissions is relatively easy to implement in farming through farm management software. Similarly, the information collected would allow monitoring NUE and N surplus as generally important indicators for agronomic and environmental farm performance, including guidance on targets to achieve *(62)*. A focus on surplus, however, does not capture all possible reductions in emissions associated with fertilizer, particularly occurring as short-lived peaks or in hotspots. It also neglects independent effects of inhibitors and controlled-release products on direct and indirect N_2O emissions, as noted above.

A final consideration is about the way to express emissions (and their reductions). Some metrics typically express emissions per unit of land area (kg N_2O-N per ha), as a GHG intensity (per unit of crop production, e.g. N_2O-N per kg grain) or per unit of N input provided (i.e. as an emission factor, kg N_2O-N per kg N applied). It is likely that all three metrics are useful depending on the aim of the emission reduction. GHG intensity and EFs are efficiency-based metrics which account for output or input, while a land-based metric does not consider the input received or output provided by the land area. For absolute emission reductions, land-based emissions are the most relevant metric. In carbon credit schemes for food supply chains, however, companies wanting to reduce the carbon footprint may prefer using per-unit-of-food (intensity-based) measures. Emissions per unit of product are also important for international trade, better suiting the application of carbon border adjustments.

Advances in N_2O emission knowledge and practices to reduce emissions indicate that mitigation following the principles of Responsible Plant Nutrition is possible and feasible. To advance implementation at the farm level, incentive mechanisms have to recognize motivations and barriers to adoption and prioritize actions. Making this happen will require commitments and aligned actions by many stakeholders.

WHO NEEDS TO DO WHAT?

Governments:

- Adopt policies that incentivize and reward adoption of practices and technologies that have proven impact on increasing N use efficiency and reducing GHG emissions, N_2O in particular, such as nitrification and urease inhibitors and controlled-release N fertilizers.
- Work with industry on last-mile delivery extension programs and emission-reporting regulations compatible with market-based approaches.
- Improve methodologies and ensure that reduction efforts are captured in national GHG inventory reports.

Industry:

- Implement targeted Scope 3 emissions reduction programs; incentivize and support the documentation of emission reductions.
- Adopt standards for reducing N_2O emissions and join voluntary carbon market schemes.
- Support and train accredited crop advisers to facilitate extension, monitoring, reporting and verification of emission-reducing practices.
- Drive innovation, as well as provide resources to develop new technologies for GHG mitigation, including smart, controlled-release fertilizers, and real-time precision N management technologies.
- On a regional basis, provide leveraged support for public research on key issues related to the 4Rs.

Carbon market participants and investors:

- Develop and refine evidence-based, transparent standards for claiming carbon credits through adoption of N_2O emission-reducing practices.
- Create and implement voluntary carbon market schemes that financially benefit farmers and stimulate wider adoption of practices and technologies that reduce N_2O emissions.

Farmers and other practitioners:

- Optimize nutrient management with available 4R practices based on crop needs and soil fertility conditions, and using appropriate decision support tools.
- Evaluate practices at the farm level; keep records and provide data on farm activities that can be used in protocols and sustainability metrics; provide technical assistance (peer-to-peer).

Researchers:

- Design and evaluate novel practices that increase NUE and reduce N_2O emissions.
- Develop and improve databases, emission factors, methodologies, and models for use in emission reduction protocols and standards.
- Evaluate cost/benefits of practices and work with farmers/practitioners to identify practices that are most feasible and practical at the farm level.

WHAT WOULD SUCCESS LOOK LIKE?

If the actions outlined in Table 4 are adopted widely enough, the following results could be achieved in the coming few decades:

1. Approximately 70% of the GHG emissions associated with fertilizer use could be mitigated by 2050. The bulk of that must be achieved in regions that account for most of the current N fertilizer use: particularly Asia, North America, and Europe.

2. The IPCC methodology for GHG emission inventories estimates N_2O emissions based on N balance rather than N rates, recognizing that N rate increases in regions of low N use increase emissions less than in regions with high rates of N use.

3. The wide adoption of practices that reduce N_2O emissions also supports further increases in crop yields and N use efficiency and reduces other losses of reactive N to the environment, thus contributing to global ambitions of halving N waste, improving water quality and protecting biodiversity.

4. Robust methods and standards have been widely adopted to account for N_2O emissions in farming, and to support carbon credit schemes that financially incentivize N_2O-reducing technologies and practices. Farmers gain from these new payment schemes and can offset costs associated with adopting new technologies and practices. Mainstreaming incentivizes industry and innovators to invest in developing even better technologies and solutions.

5. Participation by farmers in agri-food industry schemes to reduce the GHG footprint of food has led to more trust and transparency, including willingness to share data on nutrient management practices for purposes of monitoring, evaluation, and reporting of sustainability outcomes. Digital technologies are increasingly used for these purposes, including artificial intelligence.

6. Along with decarbonized fertilizer production, new product and food labels have emerged that report their full-chain carbon footprints inclusive of the portion associated with fertilizers.

7. Researchers and startups have developed novel fertilizers with minimal GHG emissions and longer-lasting modes of action for specific conditions.

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