REDUCING EMISSIONS FROM FERTILIZER USE

September 2022

IFA INTERNATIONAL FERTILIZER ASSOCIATION

Helping to feed the world sustainably

SYSTEMIQ

CONTENTS

ABOUT THIS DOCUMENT

This document is a publication from Systemiq, commissioned by the International Fertilizer Association (IFA) and funded by ten IFA members.

Systemiq is a systems change company that partners with business, finance, policymakers and civil society to make economic systems truly sustainable.

IFA is the only global fertilizer association with 400+ members and a mission to promote the efficient and responsible production, distribution and use of plant nutrients. This mission plays a critical role in helping to feed the world sustainably.

The IFA members who sponsored this report are:

- Platinum sponsors – CF Industries, Nutrien, OCP, Qafco, Sabic Agri-Nutrients and Yara
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The report was prepared by the Systemiq team, Jeremy Oppenheim, Rupert Simons, Thomas Hegarty, and Paddy Ellen, in close consultation with and technical input from IFA and the sponsoring companies, as well as discussions with academia and civil society. The sponsoring companies and IFA endorse the general thrust of the arguments made in the publication but should not be taken as agreeing with every finding or recommendation.

Any questions may be sent to ifa@fertilizer.org.

ACKNOWLEDGEMENTS

This report has benefited from extensive consultations with stakeholders and experts from around the world, including representatives from IFA and the sponsoring companies. We are grateful for their advice and guidance.

We would particularly like to thank, in addition to the representatives of the sponsoring companies, the following people who lent us their time and expertise:

- Scarlett Benson, Seth Cook and Talia Smith – Food and Land Use Coalition
- Achim Dobermann, Patrick Heffer and Alzbeta Klein – IFA
- Alison Eagle, Amy Hughes and Shelby Shelton – Environmental Defense Fund
- David Kanter – New York University
- Steven Lord – University of Oxford
- Claudia Wagner-Riddle – University of Guelph
- Xin Zhang – University of Maryland Center for Environmental Science

Jeremy Oppenheim

Founder and Senior Partner, Systemiq

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CEO/Director General, International Fertilizer Association

The world is facing a food security crisis as a result of the war in Ukraine. This comes on top of the continued challenge of transforming how we grow food to meet climate, biodiversity and other environmental goals. These challenges are urgent, and the fertilizer sector has a core role in delivering solutions.

The world today is not on track to keep global warming to less than 1.5°C. Reports from the World Meteorological Organization indicate that there is a high chance that we will exceed 1.5°C of heating within the next five years. This is not a long-term problem. It is a problem whose impacts we will start to feel more and more in the near future. It is a problem that requires action now – and we can do something about it.

The food sector is responsible for 31% of greenhouse gas emissions, with mineral fertilizers contributing around 6% of these. At the same time, the fertilizer sector has the products, expertise and global reach to contribute solutions, working with farmers and policymakers, scientists and other partners across agriculture.

We welcome this report on reducing emissions from fertilizer use. It will act as an important resource for fertilizer companies and other stakeholders interested in working with the industry to help feed the world sustainably.

Many of the measures to reduce emissions from fertilizer use are known, well understood and affordable. Many of the same measures also improve farmers' resilience, reducing exposure to volatile input markets. Improving nitrogen use efficiency helps the climate and the wider environment; it also helps food security and can support farm profitability. Expanding the applicability of inhibitors can bring down emissions further. Fertilizer companies can also expand efforts to advise farmers on how to sequester carbon in soils – and support those farmers who are already doing so.

Efforts across the wider food system to address food loss and waste, and shift consumer demand towards more nitrogen-fixing crops would further lower emissions from fertilizer use and increase end-to-end resource productivity.

Delivering emissions reductions will require a step change in the sector's current outreach work with farmers, and in its research and development. Achieving the scale required will mean building and strengthening partnerships across the sector, up and down the distribution chain, and with food companies and retailers. It will mean changing the way crops' fertilizer needs are calculated and how farmers are advised on fertilizer use. And it will mean enhanced engagement with policymakers and standard setters to change the balance of incentives for farmers in favour of low-emission practices.

There has never been a better time for the fertilizer industry to contribute to solving both short- and longer-term crises.

"I applaud the International Fertilizer Association for taking on this critical work. Farmers need support to reduce emissions from fertilizer use. For solutions to this important challenge to be durable and widely-adopted, they need to be flexible and farmer-centric, so we can help mitigate emissions, all while supporting food security. Increasing the use of enhanced efficiency fertilizers, in particular, can help reduce nitrous oxide emissions while matching crop nutrient requirements."

John Kerry
U.S. Special Presidential
Envoy for Climate

"The World Resources Institute is focused on transitioning the food system to produce enough food for everyone while staying within a 1.5°C climate budget and protecting nature. This report highlights the critical role of the fertilizer industry. Two contributions stand out. First, the role of fertilizers in helping to produce more food on the same or less land. We need to close a roughly 50% food gap between what is produced today and what will be needed to feed everyone in 2050, while halting the conversion of forests by agricultural land expansion. Second, the role of fertilizer industry in increasing yields with less inputs and externalities. This requires a step-change in nitrogen use efficiency and wide-spread adoption of controlled-release fertilizers and nitrification inhibitors. To this end, I welcome the recommendation for more research on barriers and opportunities to scaling these approaches. I am delighted to see that the fertilizer industry is developing a science-based approach to decarbonize their sector, including scope 3 emissions. This is exactly the kind of leadership that is needed to help create a sustainable food future."

Janet Ranganathan

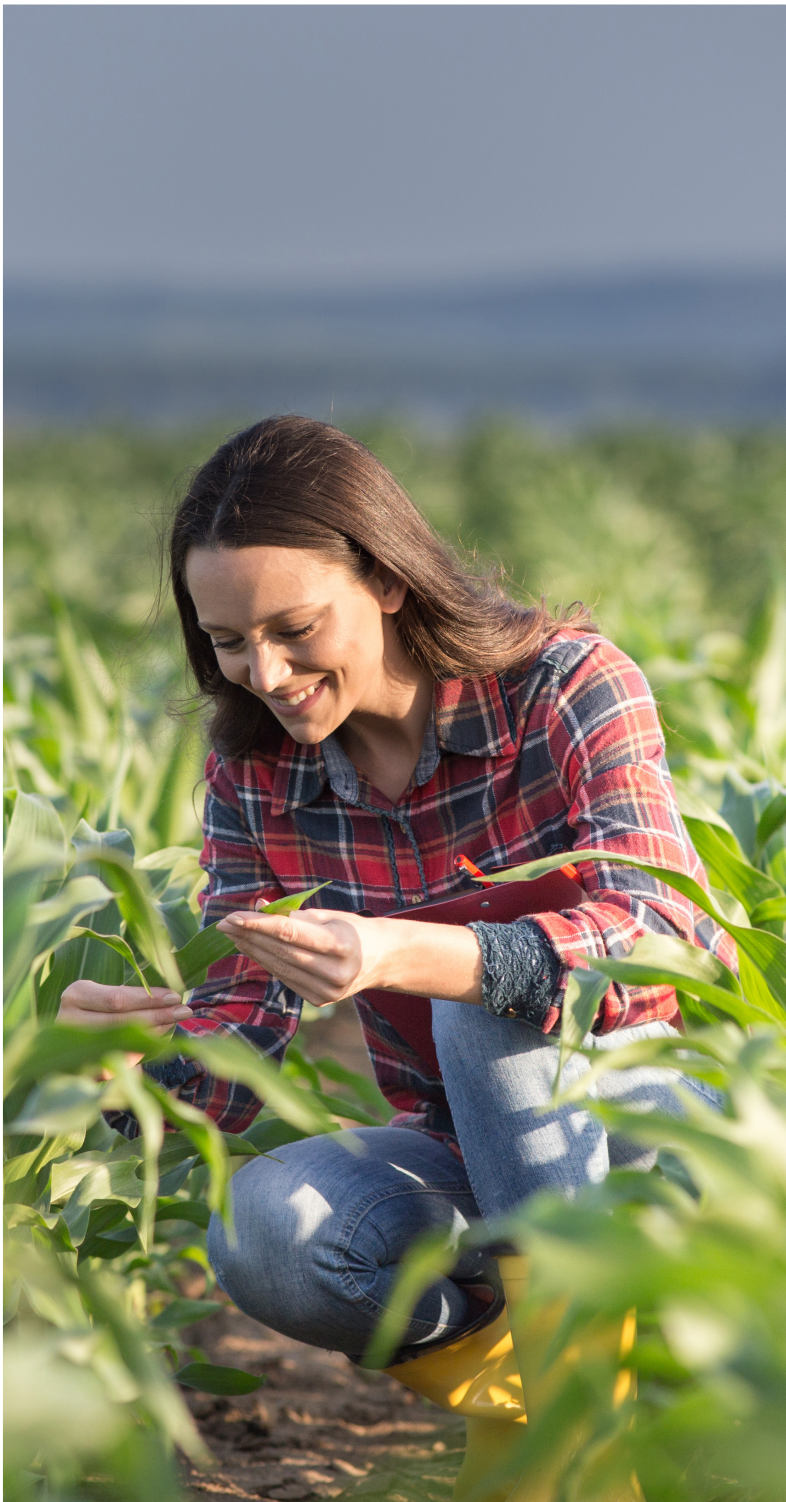
Managing Director, Strategy,
Learning & Results at the
World Resources Institute (WRI)

"Fertilizer companies play a very important role in how we transition to a regenerative and equitable food system which produces healthy, safe and nutritious food for all. The actions highlighted in this report provide a map for how fertilizer companies help accelerate this transition. WBCSD looks forward to supporting IFA and companies along the value chain to deliver on the critical transformations needed."

Diane Holdorf

Executive Vice President
Pathways at the World Business
Council for Sustainable
Development (WBCSD)

EXECUTIVE SUMMARY



Mineral fertilizers are a critical input to the global food supply chain. Availability of these essential inputs has a direct impact on the quality and quantity of food that the world produces.

Mineral fertilizer has been a key factor in boosting agricultural yields, feeding a growing population and mitigating pressure for land use change. At the same time, mineral nitrogen fertilizer use is associated with annual greenhouse gas emissions of around 0.7 billion tonnes of carbon dioxide equivalent (Gt CO_2e), alongside other forms of nitrogen pollution.

The mineral fertilizer sector is looking to address these emissions, playing its part in keeping to the Paris Agreement's 1.5°C goal, while ensuring the continued supply of fertilizers required by farmers to ensure the world's ability to feed a growing global population. Proactive efforts will also help the sector meet increasing demands for decarbonization from investors, policymakers, scientists and civil society.

The fertilizer industry is pursuing the development of a Sectoral Decarbonization Approach to enable it to set Science Based Targets for its Scope 1 and 2 emissions. This will build on existing work to decarbonize ammonia production. The purpose of this report is to examine the opportunities to reduce the industry's downstream Scope 3 emissions from fertilizer use, and the scope to support carbon removals from the atmosphere through soil carbon sequestration.

Implementing the recommendations in this report, and meeting the decarbonization challenge head-on, will help secure the long-term economic and environmental sustainability of the entire food system and create a crop nutrition sector for the future. At a time when the availability and affordability of food and fertilizer are under great pressure, it is more essential than ever to put the industry on a sustainable footing.

Increased use of mineral fertilizer and developments in the wider food system have fed the world over the past century but have led to significant greenhouse gas emissions

1. Mineral fertilizer has played a critical role in improving food security over the past century, boosting crop yields and agricultural productivity. This has helped to reduce hunger even as the global population has grown rapidly, and to contain the need for cropland expansion and associated land conversion.[a] Fertilizers are critical to addressing the UN Sustainable Development Goal 2 of reaching zero hunger. At the same time, we have seen increasing gross deforestation and expanding cropland, because of market opportunities that exceed possible yield increases on existing land or because it easier to expand cultivated land than to close yield gaps.

2. At the same time, the food system "from farm to fork" is responsible for net 17 Gt CO_2e/year,[b] 31% of human-caused greenhouse gas emissions.[1] Within this, mineral nitrogen fertilizer use is associated with around 717 Mt CO_2e/year.[c] There is considerable uncertainty around this figure given data availability, but it is similar to the total emissions from the German economy each year.[2]

3. Limiting the global temperature rise to 1.5°C[d] and achieving the United Nations' Sustainable Development Goals will require the food system, and the fertilizer sector, to change. The fertilizer sector has commissioned this report to identify ways to address emissions on-farm as a step towards this change in the food system. These emissions form part of fertilizer companies' downstream Scope 3 emissions inventory, as defined by the Greenhouse Gas Protocol.

4. The recommendations in this report build on existing activity but also require new initiatives. Farmers cannot be expected to meet the costs and burdens of cutting emissions alone. This means that the fertilizer sector needs to scale up its work with farmers, as well as with stakeholders in other parts of the food system, policymakers and standard-setters to create the right environment for better fertilizer use. This needs to happen at the same time as continuing efforts to increase yields, grow more nutritious food, improve soil health and increase soil carbon stocks.

5. Failure to act faster carries significant risks. Climate change will destabilize food production systems, increasing volatility and the financial vulnerability of fertilizer companies' customers. And the fertilizer sector is experiencing growing pressure from investors, policymakers, scientists and civil society to put in place plans to address its greenhouse gas emissions and wider environmental impact.

6. Taking voluntary action now can address these risks to the sector and cut emissions. This will allow the sector to continue to deliver its mission of feeding the world as part of the broader agri-food system, supporting farmer livelihoods and mitigating pressure for land conversion.

Many of the mechanisms to cut emissions already exist

7. Increasing nitrogen use efficiency (NUE) through best management practices is key to addressing greenhouse gas emissions from mineral fertilizer use. Mineral nitrogen fertilizer applications should synchronize nutrient supply with crop requirements and so maximize the share of nutrients taken up by the plant, thereby reducing nutrient losses to the environment.

8. NUE varies significantly across the globe. In France and the United States it is above 70%, while in China and India it is below 50%.[3] %. A realistic ambition would be to improve average global NUE in crop production from around 50% currently to 70% by 2040. This could save 190–370 Mt CO_2e in nitrous oxide emissions and 30–50 Mt of carbon dioxide in 2050, relative to a business-as-usual scenario (see Box 1).

9. The changes in practice required to improve NUE depend on local circumstances. The fertilizer sector's 4R Nutrient Stewardship programme sets out how to improve NUE by applying the right nutrient source, at the right rate, at the right time and in the right place to best meet plant needs. Farmers and nutrition advisers can use the 4R toolbox to select those practices that are most suitable to their site- and crop-specific conditions.

10. Improving NUE does not only mean optimizing nitrogen management, but also other inputs. Plants need access to the right mix of other nutrients, including phosphorus, potassium, sulphur, calcium, magnesium and micronutrients, as well as sufficient water, healthy soil and appropriate labour inputs. For example, phosphorus can improve plants' nitrogen uptake and biological nitrogen fixation, thus increasing NUE.

11. Extending the use of inhibitors and controlled-release fertilizers can further reduce nitrous oxide emissions. Urease and nitrification inhibitors slow the conversion of nitrogen fertilizer to other nitrogen compounds in the soil. Controlled-release fertilizers help match nutrient release with crop requirements. Further research and product development is needed to make these technologies more affordable, to better understand the synergies between them, and to improve understanding of wider environmental impacts. If these technologies were implemented with half of all mineral nitrogen fertilizer applied, it could cut greenhouse gas emissions by a further 100–200 Mt CO_2e in 2050, relative to a business-as-usual scenario.

12. These measures will not eliminate emissions from fertilizer use. Further reductions will depend on a wider transformation of the food system. Changing crop rotations to allow more biological nitrogen fixation could further reduce nitrogen fertilizer use, though it also requires a rebalancing of human dietary preferences and industrial processes towards increased consumption of such crops. Together, these actions could save a further 65–75 Mt CO_2e in nitrous oxide and 10–15 Mt of carbon dioxide in 2050, relative to a business-as-usual scenario. Measures to improve yield and reduce food loss and waste would also reduce emissions from fertilizer in the future.

Box 1. High level scenario for cumulative emissions reductions

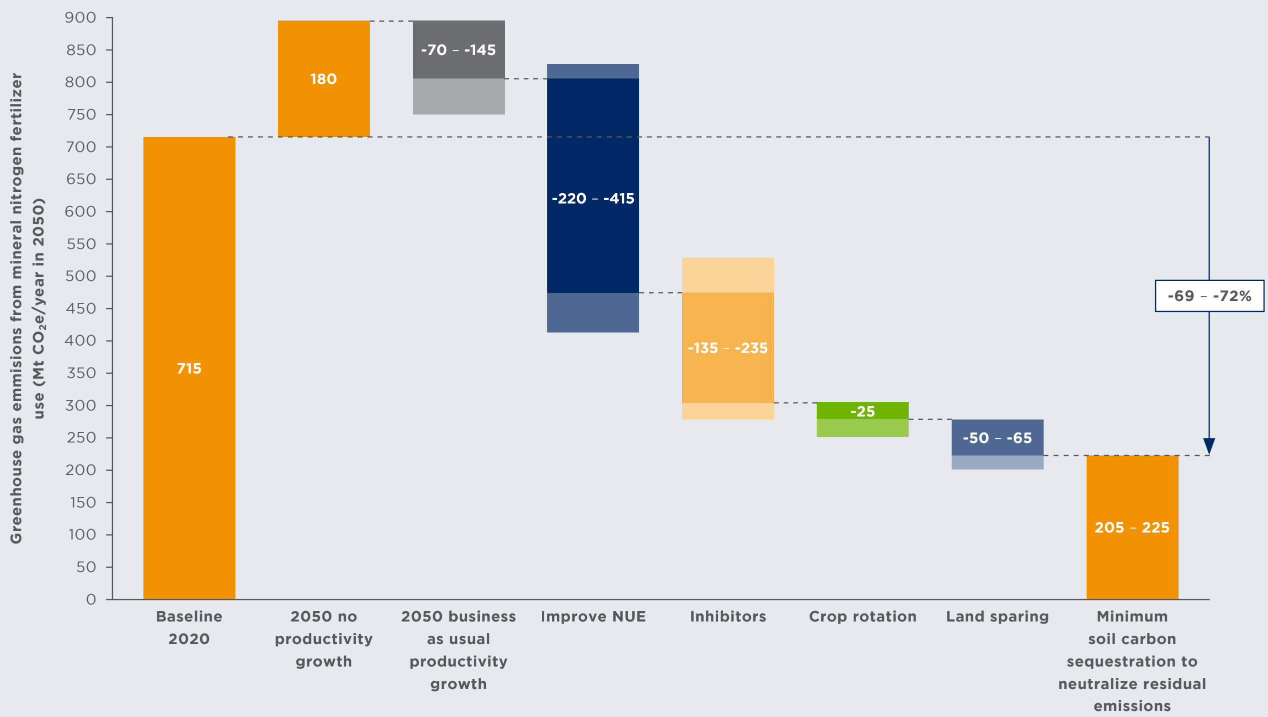
The report presents a top–down scenario for reducing greenhouse gas emissions. The aim of the scenario is to illustrate the potential of the various interventions when applied at scale over the next 30 years. It should not be taken as a forecast or statement of what should happen, nor an exhaustive list of all interventions.

Figure 1 shows the results of the analysis, constructed from three sub-scenarios with varying underlying assumptions. The first step is to create a business-as-usual scenario for 2050. In this scenario, the global population grows in line with UN projections, agricultural productivity grows 0.8%–1.1% per year, nitrogen uptake grows 0.4%–0.6% per year and the gap in mineral nitrogen application rates between Africa and the current global average closes by between one and two thirds.

Emissions-reduction measures are then applied sequentially: NUE is increased to 65%–75% through adoption of best practices; nitrification and urease inhibitors are applied to half the crop area and half the area fertilized with urea respectively, reducing direct nitrous oxide emissions on those areas by 30%–50% and the fraction of nitrogen from urea that is lost to volatilization by 30%–60%; the share of legumes in crop rotations is increased from c. 14% to 20% of global cropland; and dietary shifts allow the release of land from crop production to further reduce emissions.

Remaining emissions then need to be neutralised, potentially through supporting soil carbon sequestration.

Figure 1. High level scenario for cumulative emissions reductions



Darker bars show the core scenario, with the lighter shading showing some of the uncertainty around this result. Totals may not sum due to rounding and the way the sub-scenarios are aggregated.

Source: *Systemiq calculations*

13. Some emissions will never be eliminated. The proposed measures combined could reduce emissions to around 175–190 Mt CO_2e of nitrous oxide per year, less than 30% of current levels, and around 30 Mt of carbon dioxide, less than 40% of current levels. However, given the nature of mineral nitrogen fertilizer and microbial activity in the soil, some residual emissions will always occur. These will need to be neutralized through carbon dioxide removals from the atmosphere elsewhere for the sector to reach net zero.

14. Soil carbon sequestration is one source of carbon removals in the fertilizer sector's value chain. Estimates for the total potential carbon sequestration in soils range from 0.4–6.8 Gt CO_2/yr, with higher levels of confidence at the lower end of the scale. Maximizing this potential requires supporting farmers to adopt balanced nutrition, soil amelioration, and other best management and regenerative agricultural practices to improve soil structure and allow more biomass to be grown and incorporated into the soil. The stable carbon-to-nitrogen ratio in soil organic matter means that more nitrogen is needed to create the microbial conditions to decompose biomass to carbon. Phosphorus also plays a key role in increasing soil carbon under tropical phosphorus-fixing soils; these are widespread and have high biomass production and carbon sequestration potential.

15. The sequestration required to neutralize residual emissions from fertilizer use is equivalent to around a third of the Intergovernmental Panel on Climate Change's central estimate for cost-effective soil carbon sequestration on cropland.[4] Only removals projects that use a corporate accounting approach and are within the company's supply chain can count as insets. Inevitably, trade-offs between sequestering carbon in soils and nitrous oxide emissions need to be taken into account, as should the wider benefits from improved soil health.

There are significant emissions-saving opportunities across regions with benefits to farmers

16. Action is needed in all markets to reduce emissions and improve productivity. In China there remains excessive use of mineral nitrogen fertilizer, especially in smallholder farming systems and fruit and vegetable production. In India, fertilization is too weighted towards nitrogen with insufficient supply of other nutrients. In the United States and Europe there remains scope to push up efficiency through increased adoption of best fertilization practices, as well as additional opportunities from innovative products. In some parts of Africa and Latin America, additional mineral fertilizer will be required. Around the world there are opportunities from wider food system changes to reduce emissions further.

17. Many of these actions are cost-saving for farmers, but other barriers across the food system hold back implementation. Increasing NUE can reduce input costs and increase yields in many cases, improving farmers' financial positions. Farmers can also generate income from soil carbon sequestration through sale of credits, (including to their customers and suppliers who have set targets to reduce scope 3 emissions) strengthening financial returns from best practices, while also improving farming's wider environmental sustainability.[e]

18. However, farmers operate as part of a wider system and many face barriers to changing their business practices, often outside their control. Among the most prevalent hurdles are: lack of time, knowledge or resources to apply best practices; financial barriers to accessing required technology; constrained local labour markets; lack of agronomic advisers with appropriate credentials, professional agronomists, certified crop advisers, or other recognized agricultural credentials; lack of support among peer networks; insufficient sale price premiums associated with low emission practices or access to markets where there are; and the cost of measures such as application of inhibitors.

A roadmap to realizing these opportunities for reducing emissions

19. This report from Systemiq, commissioned by the International Fertilizer Association (IFA) sets out a roadmap of actions for the fertilizer sector. The proposals can help to realize emissions-reduction opportunities, mitigate the growing risks, and address the greenhouse gas emissions associated with the use of mineral fertilizer in the field. It will be followed by detailed work to develop a sectoral decarbonization approach and Scope 3 guidance and target-setting under the Science-Based Targets initiative, and associated company commitments. Box 2 outlines how the fertilizer sector's emissions can be divided across the different emissions scopes.

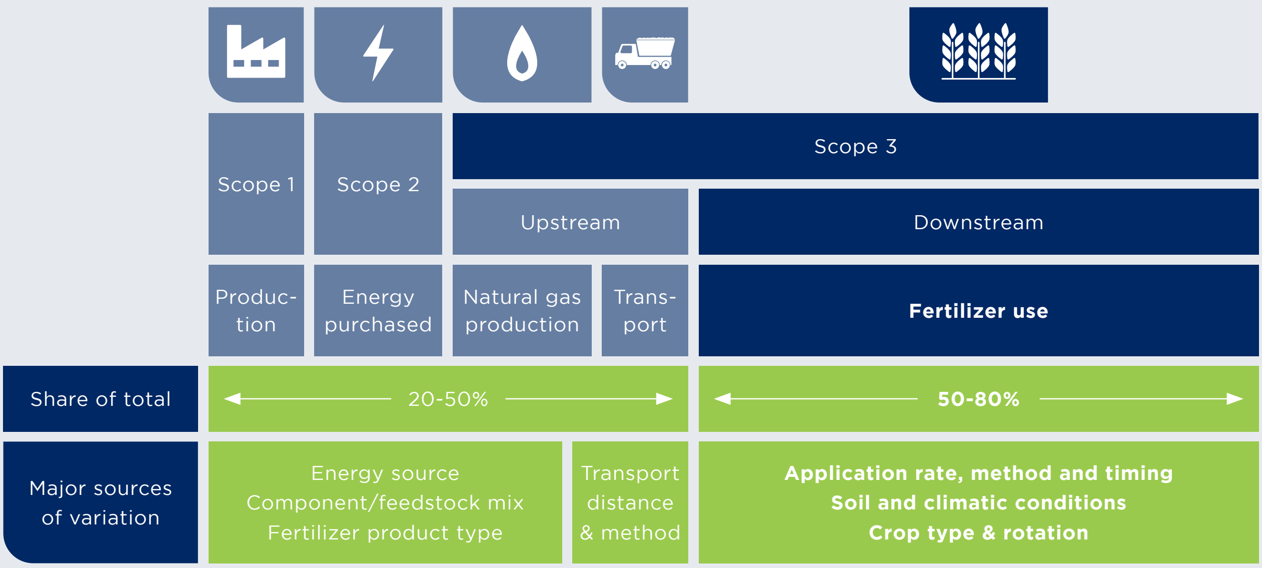
Box 2. Fertilizer sector emissions and the Greenhouse Gas Protocol

The Greenhouse Gas Protocol provides a standard against which companies can report their emissions. This provides a snapshot of performance for a given reporting period. The protocol divides corporate emissions into three “scopes”:

- **Scope 1: Direct greenhouse gas emissions.** These are emissions that occur from sources that are owned or controlled by the company, such as the emissions from use of natural gas and other fossil fuels in the production of mineral nitrogen fertilizer or precursor products;
- **Scope 2: Electricity-related indirect greenhouse gas emissions.** These are the emissions associated with the production of electricity used by a company; and
- **Scope 3: Other indirect greenhouse gas emissions.** These are emissions that are consequences of the company’s activities, but occur from sources not owned or controlled by the company, both upstream and downstream in the value chain, including use of the company’s products.

Figure 2 shows the distribution of emissions across these different scopes for a fertilizer manufacturer. The focus of this report is downstream scope 3 emissions.

Figure 2. Fertilizer sector emissions



Source: *Nutrien, IFA, FAOSTAT, World Business Council for Sustainable Development and World Resources Institute (2004).*

20. Farmers will be key to realizing these opportunities, and solutions have to be farmer-centric. Farmers stand to benefit from many of the efficiency-improving measures through reduced input costs and improved yields. However, some enhanced products come with a price premium, and wider changes to the food system will also depend on changes to consumer preferences. The regional analysis in this report suggests that 25%–30% of the abatement measures would be cost saving for farmers.

21. Fertilizer companies acknowledge the shared responsibility to help farmers reduce emissions. This means working with farmers and distributors, policymakers, advisory bodies and other agri-food system actors to ensure that farmers have the incentives, resources, knowledge and products to implement the required measures.

22. The steps each fertilizer company can take depend on their place in the supply and value chain, and on the markets they operate in. Some fertilizer manufacturers will be better placed to improve the product mix available. Those with retail and distribution arms can work more directly with farmers and farm advisers. All can partner with food manufacturers and retailers to share best practices and ensure farmers see a financial return on reducing emissions; and all can participate in industry-wide initiatives to address emissions. Some actions listed may not contribute to a reduction in a company's Scope 3 emissions under the current accounting frameworks but will still support the emissions reductions demanded by policy actors and others. Key actions are summarized in Figure 3 and include:

i. **Supplying tailored products, nutrient blends and enhanced fertilizer products:** Fertilizer companies should develop and promote products optimized to minimize emissions and support soil carbon sequestration, according to different climate conditions, soil types and crops. They can offer tailored mixes of nutrients, work to improve the applicability, availability and take-up of enhanced fertilizers, and ensure distribution chains have the incentives and expertise to sell these products. Companies need to address price barriers to product adoption, for instance by promoting co-benefits beyond yield;

ii. **Educating and incentivizing farm advisers, input retailers and farmers themselves to make sustainable nutrient choices:** Fertilizer companies should work with their farm advisers and agri-input retailers, and farmers directly, to develop and promote the products, tools and software they need to address emissions and sequester carbon. New incentive structures are needed in commercial relationships with advisers, retailers and farmers to ensure that emissions reductions and removals are adequately incentivized. Additionally, tools and algorithms for determining fertilizer application need to take account of emissions and soil carbon impacts;

iii. **Pursuing in-house R&D, pre-competitive collaboration for innovation, and partnerships with research institutions:** Technical and cost barriers to reducing emissions from mineral fertilizer may be overcome through increased R&D addressing:

- local barriers to farmer uptake of best practices;
- continued improvements to the affordability, effectiveness and environmental sustainability of enhanced fertilizers;
- genetic improvements to enhance plant nutrient uptake; and
- temporally and spatially scalable nitrous oxide emissions and soil carbon measurement.

Innovation can take many forms, from in-house R&D, to collaboration with start-ups, ag-tech companies and public institutions. Industry-wide initiatives such as IFA's Smart & Green platform or competitions can also play an important role. The right form of innovation depends on the problem at hand, timespan, partnering institutions' expertise, and competition considerations;

iv. **Participating in nutrient stewardship collective outreach programmes:** No single fertilizer company can reach all the farmers needed to achieve emissions targets. The sector could collectively fund outreach activities to promote emissions reduction practices and soil carbon sequestration. Activities would be tailored to each region, working in partnership with existing advisory infrastructures, and through innovative channels. This would build on the sector's existing initiatives such as 4R Nutrient Stewardship and the EU Nitrogen Expert Panel. Collaborations within the fertilizer industry could draw inspiration from advisory bodies such as the Grains Research and Development Corporation in Australia, and extended producer responsibility schemes to manage plastic and other waste;

v. **Working with standard-setters to develop high-quality farm certifications and metrics, and carbon credits for nutrient management:** Farm certification schemes are one way that farmers can unlock higher value for their products. In addition, measurement, reporting and verification bodies, and voluntary carbon market organizations set standards for soil carbon sequestration credits. Fertilizer companies can help these standard-setters in developing robust criteria and metrics for nutrient management and fertilizer best practices. Such actions can support market transparency for the sector's emissions, develop carbon farming and ensure high-quality carbon credits;

vi. **Supporting policies consistent with emissions reductions and advising policymakers on how to incentivize and implement them:** Public policy has an important influence on farmers' business decisions. Some established policies, having achieved their initial objectives, now create perverse incentives for inefficient fertilizer use and should be reformed. In other areas, new regulations, payments or emissions pricing schemes may be needed. The appropriate levers will vary by geography and farm type, and those making reforms should carefully consider the impacts on farmers. The fertilizer sector should scale up work with policymakers to ensure they are aware of the opportunities from better fertilization and to advance policy reforms to support this goal;

Figure 2. Actions for fertilizer companies to address emissions alone and in coalition

<table>
<tr><th></th><th>Fertilizer manufaturer</th><th>Fertilizer traders and blenders</th><th>Fertilizer sellers</th></tr>
<tr><td rowspan="6">Individual companies</td><td colspan="3">Improve understanding of the distribution chain</td></tr>
<tr><td></td><td></td><td>Educate and incentivise advisers, input suppliers and machinery providers for sustainable nutrient choices</td></tr>
<tr><td></td><td></td><td>Advise farmers on good practices</td></tr>
<tr><td>Supply enhanced fertilizer products</td><td></td><td></td></tr>
<tr><td colspan="2">Supply tailored nutrient blends</td><td></td></tr>
<tr><td colspan="3">In-house R&D</td></tr>
<tr><td rowspan="3">Fertilizer sector together</td><td colspan="3">Nutrient stewardship collective outreach programmes</td></tr>
<tr><td colspan="3">Pre-competitive innovation initiatives (e.g., challenge prizes)</td></tr>
<tr><td colspan="3">Work with standard setters to develop high quality farm certification criteria and robust evidence bases for carbon credit issuance for nutrient management</td></tr>
<tr><td rowspan="3">In coalition with the food chain and policy makers</td><td colspan="3">Form partnerships with research institutions to influence priority areas for research</td></tr>
<tr><td colspan="3">Commercial partnerships with and advice for food companies to reward farmers for making changes to practices
Commercial incentives for farmers to adopt best fertilizer and wider farm management practices</td></tr>
<tr><td colspan="3">Advocate policy reforms that better support emissions reductions
Advise policymakers on priorities and what is possible</td></tr>
</table>

vii. **Building relationships and coalitions for emissions reductions along the distribution chain:** The fertilizer distribution chain is complex, with mixing of products, and trading between fertilizer manufacturers, blenders and retailers. Companies need to understand how and where products are used to identify and report value-chain mitigation actions. The fertilizer sector should work to strengthen relationships and build coalitions along the distribution and value chain to improve understanding of how fertilizer is used, where there are gaps; and

viii. **Partnering with food companies and retailers to reward farmers for making changes to practices:** In-field emissions from mineral nitrogen fertilizer sit within food companies' and retailers' upstream Scope 3 inventories. Food companies can create a commercial motivation for farmers to address emissions by setting procurement standards or other incentives to foster positive climate action. Enforcing these can be challenging, but fertilizer companies can advise farmers on best fertilizer practices and supply tailored products. Fertilizer companies, food companies, retailers and farmers can work together to promote low-carbon food products to help meet growing market demand for such products.

23. The fertilizer sector should reflect on these proposals and use them to inform company and sector-wide targets. Next steps may include commitments by leading companies at the COP27 United Nations climate summit in Egypt in November 2022. Following this, the adoption of the forthcoming Sectoral Decarbonization Approach and Scope 3 emissions guidance and target setting being developed by the Science Based Targets initiative (SBTi) will be an even bigger step, covering Scope 1, 2 and 3 emissions. The fertilizer sector should press ahead with implementing changes and present the first emerging results at COP28 in the United Arab Emirates in November 2023. These initiatives should be complemented by government action to review and refocus food, farming and fertilizer subsidies and to support collaboration across the food and farming sectors to address emissions.

NOTES

a. The number of calories available per person per day increased from 2,196 in 1961 to 2,884 in 2013, while the population grew from 3 to 7 billion.

FAO. (2013). Food Balances (-2013, old methodology and population). FAOSTAT. https://www.fao.org/faostat/en/#data/FBSH.

The impact of mineral fertilizer is difficult to quantify, but some estimates indicate that half the global population is now fed by mineral fertilizer, and that if global crop yields had stayed at their 1961 levels, an additional 1.3 billion ha would have needed to be converted to arable land by 2014 to match production increases. These estimates only consider tonnes of food production, not the food's nutritional content, which some evidence indicates could have declined over the period.

Erisman, J. W., Sutton, M. A., Galloway, J., Klimont, Z. & Winiwarter, W. (2008). How a century of ammonia synthesis changed the world. *Nature Geoscience*, 1:10, 636–639. In Ritchie, H. & Roser, M. (2013). Fertilizers. Our World in Data. https://ourworldindata.org/fertilizers. Accessed 22 April 2022.

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Shewry, P. R., Pellny, T. K. & Lovegrove, A. (2016). Is modern wheat bad for health? Nature Plants, 2:16097, 1–3. https://doi.org/10.1038/NPLANTS.2016.97.

b. These are net figures. Gross emissions are higher: the Food and Land Use Coalition estimates removals by land systems as 24.2 Gt CO_2e.

Food and Land Use Coalition. (2021). Why Nature? Why Now? www.foodandlandusecoalition.org/wp-content/uploads/2021/10/Why-Nature-PDF-FINAL_compressed.pdf. Accessed 20 July 2022.

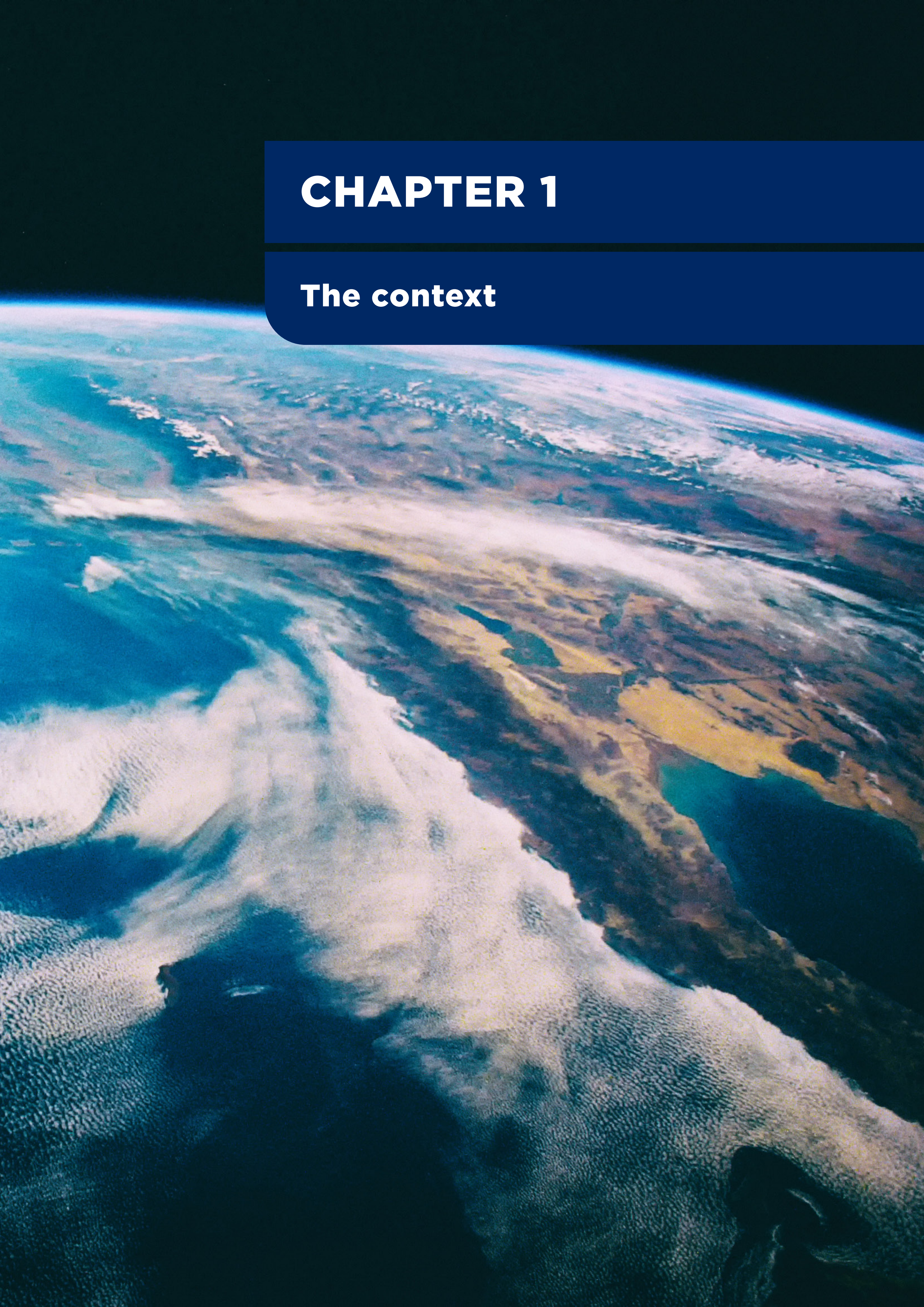
c. Under the 2015 Paris Agreement, countries agreed to cut greenhouse gas emissions with a view to "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels".

d. Part of a set of ambitions approved by IFA's Board of Directors on 25 May 2021.

e. Once a credit has been sold outside the supply chain, the fertilizer sector cannot count the sequestration towards Scope 3 emissions reductions.

CHAPTER 1

The context



The food system is a significant source of greenhouse gas emissions. Mineral fertilizer makes a critical contribution to food production, enabling the same amount of staple crops to be produced on a smaller area of land. However, mineral nitrogen fertilizer use is also associated with nitrous oxide and carbon dioxide emissions. Policymakers and investors are increasingly expecting sectors and companies to have credible plans to decarbonize their businesses in line with the Paris Agreement. The fertilizer sector is preparing a Sectoral Decarbonization Approach to allow it to set science-based targets for emissions reductions, building on existing work to support farmers to adopt best practices for fertilizer use. There are challenges with measurement of emissions from mineral fertilizer use in the field, but this should not hold back scaling up and broadening implementation of measures that are known to help reduce such emissions.

Countries around the world have committed to action to limit climate change to 1.5°C

1. Anthropogenic climate change is an existential threat to humanity. In 2015, almost all nations signed the historic Paris Agreement to hold the increase in global average temperatures to well below 2°C above pre-industrial levels and to pursue efforts to limit the rise to 1.5°C.

2. Implicit in this target is a requirement to reduce greenhouse gas emissions to net zero by the second half of this century, with around 40–50% of this decline to be achieved by 2030.[1] Hitting this target will mean reducing gross emissions to the greatest extent possible, and then offsetting any remaining emissions by removing them from the atmosphere for the long term.[2]

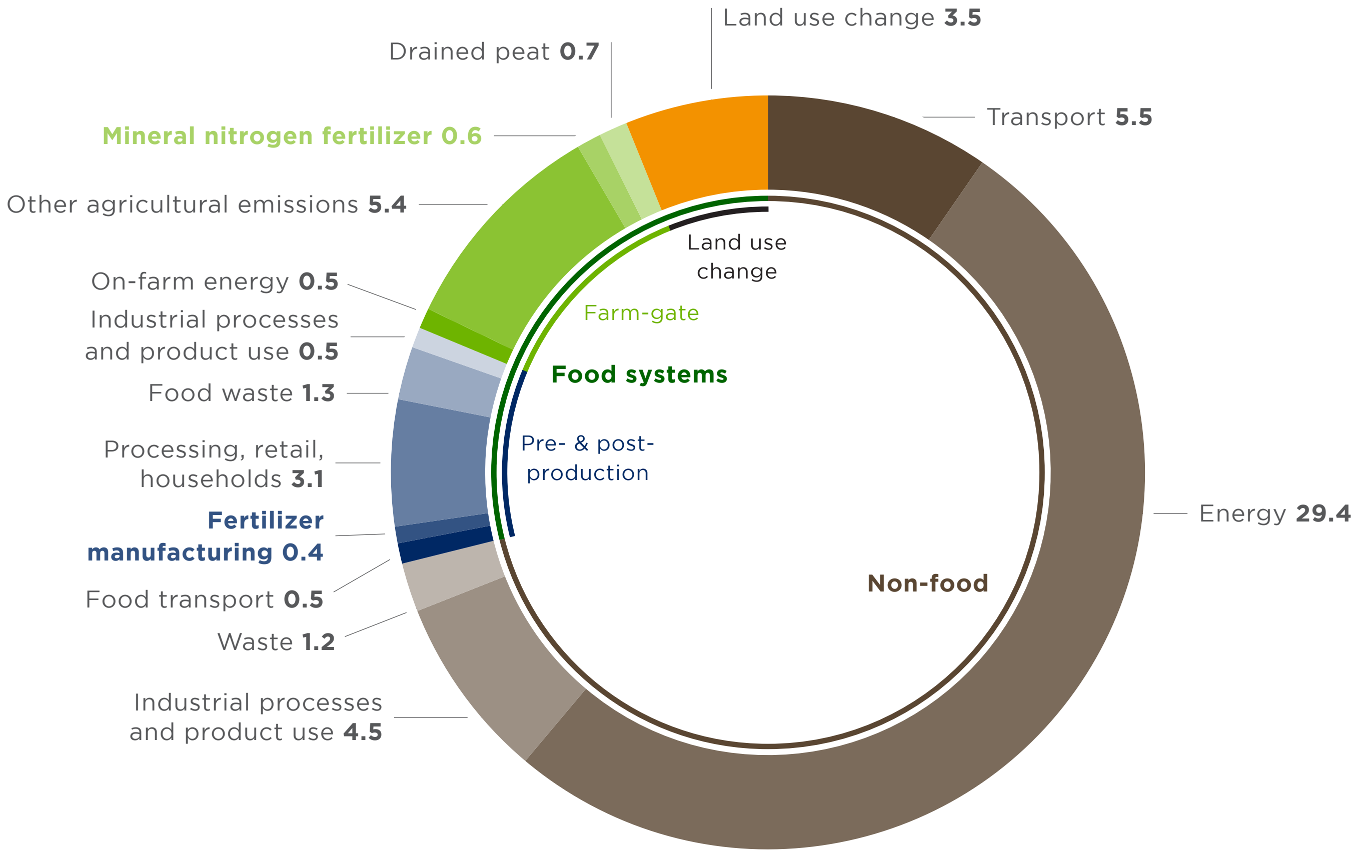
The agri-food sector has an important role to play in meeting this challenge

3. The agri-food sector needs to decarbonize if the world is going to meet the Paris Agreement targets. This will be a major challenge for the next 30 years: the agri-food sector will need to address its emissions, while producing enough nutritious food for a growing population, allowing space for afforestation and habitat protection, responding to changing consumer behaviour and dealing with the effects of climate change.

4. Decarbonizing the food sector is a big challenge. The Food and Agriculture Organization of the United Nations (FAO) estimates that the food supply chain, from farm to fork, was responsible for 31% of human-caused net greenhouse gas emissions in 2019, or 16.5 Gt CO_2e/yr (Figure 1):

- 7.2 Gt CO_2e/yr were the result of on-farm activities (organic soils, crop residues, enteric fermentation, manure, rice cultivation and mineral nitrogen fertilizer use);
- 5.8 Gt CO_2e/yr resulted from activities up and down the supply chain (transport, processing, packaging, fertilizer manufacturing, household consumption, retail and waste); and
- 3.5 Gt CO_2e/yr were from land-use change (net forest conversion, tropical forest fires and peat fires).[a] [3]

Figure 1. Food system emissions in context. Greenhouse gas emissions by source (Gt CO_2e)



The emissions from mineral nitrogen fertilizer use in this chart are lower than those listed in Table 1. This reflects FAO's use of the IPCC's 2006 emissions factors and 2014 global warming potential figures.

Source: *Tubiello, F. et al. (2021); FAO (2021); FAOSTAT.*

5. At the same time as reducing its gross emissions, the agri-food sector can help to address climate change by increasing the removal and storage of carbon dioxide from the atmosphere as woody plants and in soils. Many sectors across the economy will struggle to eliminate their gross emissions entirely by 2050, meaning they will need these carbon removals to offset their remaining emissions and so reach net zero. Estimates for the cumulative demand for removals between now and 2050 range from 70 to 225 Gt CO_2, with the higher end of the range appearing more likely. A further 3–5 Gt CO_2/year will be required after 2050 to neutralize ongoing annual emissions after 2050. Given the competing demands for land, limited capacity for soil to hold carbon and uncertainty around the affordability of engineered carbon removals, any removals are additional to deep decarbonization across all sectors – rather than a substitute for it.[4]

Mineral fertilizer contributes to the emissions, but also to the potential solution

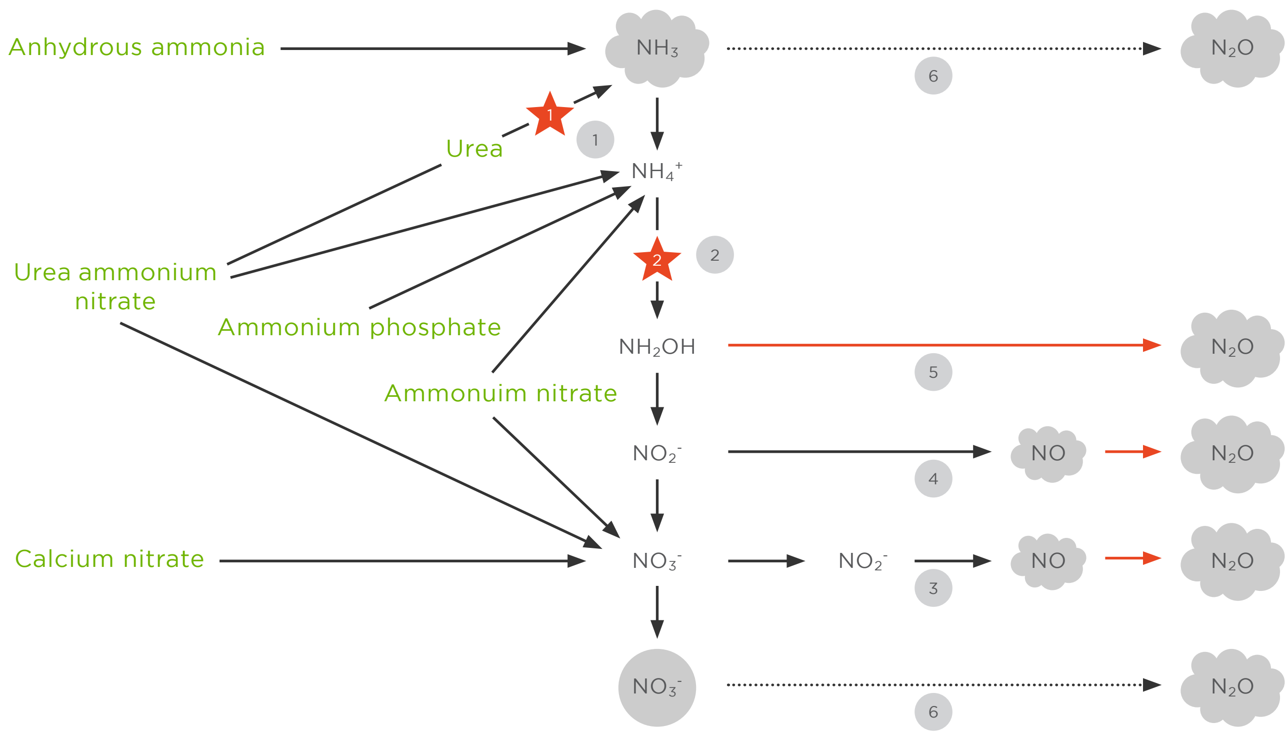
6. Mineral fertilizer plays a vital role in improving crop yields, producing food for the world's population on a constrained land area, thereby reducing the need to expand cropland for staple crops. The extent of this impact is difficult to assess,[5] but one estimate suggests that an additional 1.3 billion ha of cropland (an area 4 times the size of India) would have been required in 2014 to match production increases, measured as tonnes of food, if global crop yields had stayed at their 1961 levels, with consequent greenhouse gas emissions and biodiversity loss.[6] Nevertheless, over that period, we have still seen increasing gross deforestation as market opportunities exceed possible yield increases on existing land or it easier to expand cultivated land than to close yield gaps.

7. Mineral fertilizer also contributes to the agri-food sector's emissions, both through the mining and manufacturing process, and as a result of on-farm emissions from the use of mineral nitrogen fertilizer. Manufacturing of mineral fertilizer produced around 408 Mt CO_2e of greenhouse gas emissions in 2019, around 0.8% of total global greenhouse gas emissions.[7] These emissions primarily result from the use of fossil fuels in the production of mineral nitrogen fertilizer,[b] primarily carbon dioxide, but also methane and nitrous oxide.[8] Further emissions are associated with mining, packaging, distribution and transport of the product.

8. The most significant greenhouse gas emissions associated with mineral fertilizer occur when mineral nitrogen fertilizer is applied to the soil.[c] This stimulates microbial activity and leads to nitrification and denitrification of the fertilizer compounds (Figure 2), eventually breaking down a proportion of the ammonia and nitrates not captured by the plants into nitrous oxide,[9] a greenhouse gas 273 times more powerful than carbon dioxide,[10] and that also depletes ozone. Partitioning nitrous oxide emissions' source pathways between nitrification and denitrification can be challenging, but where conditions favour denitrification, the resulting nitrous oxide emissions are by and large higher than those from nitrification.[11]

9. Further nitrous oxide emissions can occur as part of two indirect processes. First, the volatilization of ammonia and nitrogen oxides with subsequent redeposition of these gases on land and water bodies. Second, the leaching and runoff of nitrates. These compounds then face the same denitrification or nitrification risks.[12]

Figure 2. Nitrous oxide (N_2O) emissions from soils



Pathways from fertilizer products (in green) to microbial nitrous oxide production in soil: 1) urea hydrolysis, 2) nitrification, 3) denitrification, 4) nitrifier denitrification, 5) nitrifier nitrification, 6) indirect nitrous oxide emissions associated with ammonia and nitrate loss to the environment. The red stars indicate processes inhibited by 1) urease inhibitors and 2) nitrification inhibitors.

Source: *Burton, D. and Land Resource Consulting Services (2018) "A Review of the Recent Scientific Literature Documenting the Impact of 4R Management on N_2O Emissions Relevant to a Canadian Context". Prepared for Fertilizer Canada.*

10. The final source of in-field emissions occurs specifically where urea-based fertilizers are used. When urea is applied to the soil in the presence of water and urease enzymes, the carbon dioxide that was fixed into the urea molecule during manufacturing is released through hydrolysis.[13] These emissions are intrinsic to the chemical structure of urea and are unavoidable. The role of urea is discussed further in Box 1.

11. Beyond greenhouse gases, inefficient use of fertilizers is associated with eutrophication of water bodies and air quality issues. These problems also make it harder to achieve the UN's Sustainable Development Goals, and further strengthen the case for action.

Box 1. The role of urea

Urea ($CO(NH_2)_2$) is the most widely used mineral nitrogen fertilizer globally, accounting for around half of all mineral nitrogen applied.[14] It is the mineral fertilizer with the highest nitrogen content, at approximately 46%, is widely available, affordable, and safe to use and transport. This means it plays a hugely important role in agricultural productivity and food security.

Manufacturing urea requires ammonia and carbon dioxide, itself a by-product of ammonia production. Reusing the carbon dioxide in this way means that urea has lower production emissions than other nitrogen fertilizer products. However, as urea breaks down on application to soil, this carbon dioxide is mostly re-released to the atmosphere, though a small amount may be absorbed by the crop canopy or soil microbes. The Intergovernmental Panel on Climate Change (IPCC) estimates that 0.73 t CO_2 are released per tonne of urea, based on the carbon content of the urea molecule. Where data is available, reporting entities can use alternative approaches, recognizing that some of the carbon from urea may remain in the ground.[15]

Although urea-based fertilizers are the only type associated with carbon dioxide emissions in use, that does not necessarily give them the highest overall emissions. For example, urea fertilizer may have lower nitrous oxide emissions than nitrate-based fertilizers on grasslands, peat soils, clay soils and in wet conditions.[16]

There are also ways to address some of the nitrous oxide emissions from urea. Application of best practices such as the sector's 4R Nutrient Stewardship[17] will help to minimize losses and maximize the amount of nitrogen absorbed by the plant. Urease inhibitors help to slow ammonia volatilization – something that urea has a higher potential for than other mineral nitrogen fertilizers.[18] (Volatilized ammonia is a potential source of air and water pollution and an indirect source of nitrous oxide.) In addition to inhibitors, coated fertilizers mechanically control the release of nitrogen to the soil and so can increase plant nitrogen uptake and reduce losses. Slow-release fertilizers (largely based on urea formaldehyde) can also extend the release of nitrogen and achieve higher nitrogen use efficiency.

Such measures are already in use. In India, since 2015, all subsidized urea has been coated with neem oil,[19] which has nitrification inhibitor properties. Since 2020, Germany has required that all urea is either incorporated into the soil or combined with urease inhibitors.[20]

Urea's suitability to certain soil and climate conditions and other practical advantages mean that its full lifecycle emissions may be lower than alternatives, particularly where it can be used with inhibitors. The development of a new generation of cost-effective, high performance, biodegradable coatings could also allow increased take-up of controlled-release fertilizers.

Policymakers and investors increasingly expect companies to have plans in place to make their businesses consistent with a 1.5°C scenario

12. Policymakers are increasingly taking action to drive forward decarbonization across national economies. Investors are also increasingly recognizing the impact that requirements to decarbonize will have on their investments should they not take action now in order to get ahead of such initiatives; the impacts that unmitigated climate change would have on their portfolios as a whole; and the opportunity they have, through the funds they manage, to redirect activity towards more sustainable practices.[21]

13. This is resulting in a shift in the emphasis of public policy away from focusing on food production, farmer livelihoods and trade towards more balanced policy packages, including climate mitigation and other environmental impacts, tailored to national circumstances.

14. Nationally Determined Contributions (NDCs), which set out each country's emissions reduction plans under the Paris Agreement,[22] still do not consistently include commitments and actions to reduce emissions and increase carbon sinks from the land use sector, but there are examples of good practice. Colombia's NDC annex includes targets across the food and land use system, policies associated with these targets and the responsible institutions. Ethiopia's sets out mitigation goals and actions for agriculture and land use.[23]

15. Beyond the NDCs, there are further examples of policy changes towards improving agricultural sustainability, such as in the European Union's Green Deal, the new United Kingdom's Environmental Land Management Schemes, and China's efforts to improve fertilizer use.[24] Trade policy is also starting to take environmental impacts into account, with the European Union and United Kingdom looking to introduce due diligence provisions to prevent deforestation associated with imports of key commodities.[25] Finally, the academic policy debate is also looking for ways to shift incentives for actors across the agricultural system, including fertilizer companies.[26]

16. Investors also increasingly expect companies and sectors to have credible plans in place to make their business activities consistent with a 1.5°C warming scenario. This means putting in place plans for adopting renewable energy, increasing energy efficiency and reducing emissions from industrial processes. These actions, along with R&D programmes and changes in product mixes, will help to minimize gross emissions and offset any remaining emissions. It also means adhering to the mitigation hierarchy, focusing first on reducing emissions within the company's value chain before looking to compensation or emissions neutralization measures. Sectors with land-based impacts should also prioritize interventions that preserve and enhance existing carbon stocks, within and beyond the value chain, before looking to compensatory measures for damage.[27]

17. There is an emerging governance for such plans. The Greenhouse Gas Protocol provides a standard against which companies can report their emissions. This provides a snapshot of performance for a given reporting period. The protocol divides corporate emissions into three "scopes":

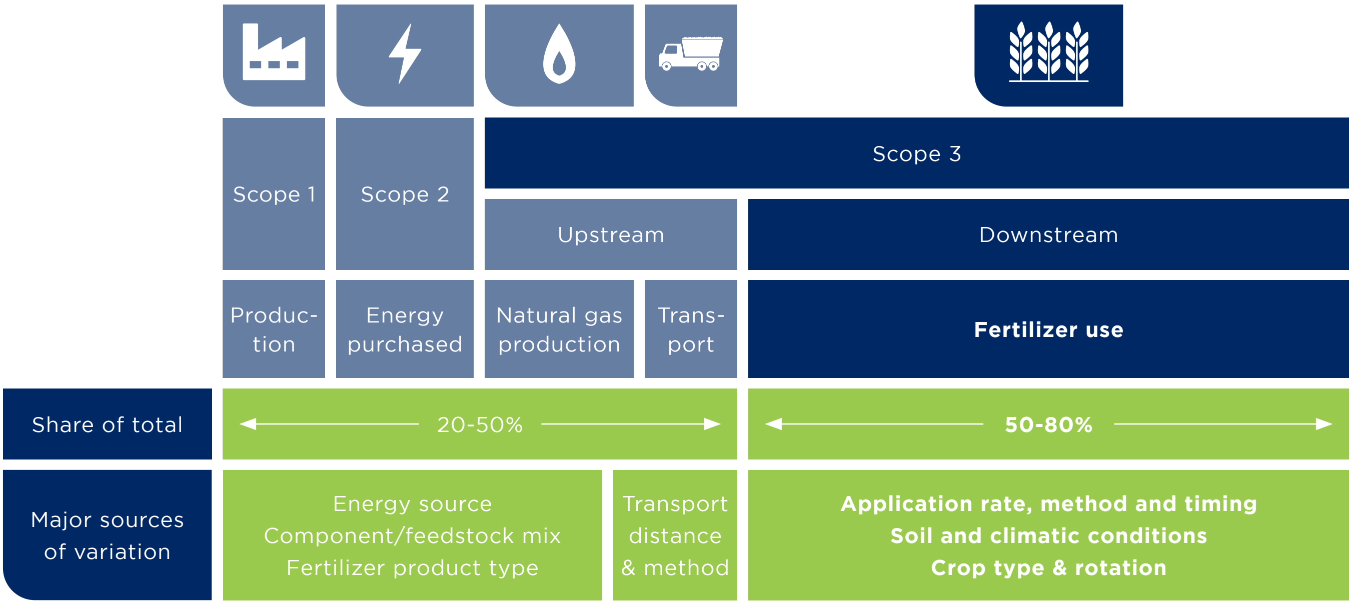
- **Scope 1: Direct greenhouse gas emissions.** These are emissions that occur from sources that are owned or controlled by the company, such as the emissions from use of natural gas and other fossil fuels in the production of mineral nitrogen fertilizer or precursor products;
- **Scope 2: Electricity-related indirect greenhouse gas emissions.** These are the emissions associated with the production of electricity used by a company; and
- **Scope 3: Other indirect greenhouse gas emissions.** These are emissions that are consequences of the company's activities, but occur from sources not owned or controlled by the company, both upstream and downstream in the value chain, including use of the company's products.[28]

18. Companies can further report sequestration of atmospheric carbon,[29] but how this should be considered as part of the above framework is still under development: the Greenhouse Gas Protocol is developing guidance for land sector emissions and removals for publication in early 2023.[30]

19. Companies can use the emissions reported under this framework as a baseline and metric for setting emissions reductions targets. The Science Based Targets initiative (SBTi) provides a methodology to do this, setting targets for reducing these emissions over time at a pace consistent with the Paris Agreement.[31] Targets must be consistent with a mitigation hierarchy and require deep decarbonization of operations and the supply chain, with removals of greenhouse gases from the atmosphere only permitted to neutralize any residual emissions that it is not possible to abate.[32] These methodologies continue to be refined and expanded: the Sectoral Decarbonization Approaches being developed since 2015 set out bespoke pathways and guidance for specific sectors to decarbonize.

20. The fertilizer sector has already taken initiatives to address its emissions. Fertilizer companies have longstanding programmes working with farmers to support efficient mineral fertilizer use and balanced nutrition, such as 4R Nutrient Stewardship.[33] The sector also collaborated with the International Energy Agency to consider options to reduce emissions associated with production.[34] Several major fertilizer manufacturing companies have committed to decarbonize their production and work to reduce upstream Scope 3 emissions.

Figure 3. Fertilizer sector emissions



Source: *Nutrien, IFA, FAOSTAT.*

21. A Sectoral Decarbonization Approach is now in development for the chemical sector, which will allow individual fertilizer companies to set science-based targets, reinforcing and supporting efforts to put their businesses on a sustainable footing for the long term.

22. This is happening alongside guidance under development from SBTi for the forest, land and agriculture sectors. This will allow companies with more than 20% of revenue, or more than 20% of total emissions under Scopes 1, 2 and 3 coming from forest, land or agriculture, to set targets that will cover both emissions and greenhouse gas removals for their activities in the land sector.[35]

23. This report focuses on opportunities to reduce the fertilizer sector's Scope 3 emissions in the field, considering the extent to which emissions might be reduced and actions fertilizer companies can take to try to realize those reductions, as well as the scope for fertilizer companies to support carbon sequestration in soil.

It is difficult to measure both nitrous oxide emissions from fertilizer use and atmospheric carbon sequestered by soils accurately

24. Measuring nitrous oxide emissions can be difficult. The emissions occur from biological processes, so vary widely over time and geography, depending on soil and climatic conditions. Measuring them in the field is costly and not scalable, requiring the installation of static chambers to monitor the gases released from small areas of soil. This makes getting good spatial and temporal coverage across the world's crop areas very difficult, meaning that individual measurements may not be representative of large areas over many years.

25. The expense and inconvenience of measuring nitrous oxide directly means that modelling approaches, such as the use of emissions factors or biogeochemical models, tend to be used for large-scale emissions estimates. Inevitably, these are only approximations of actual emissions, given the lack of consistent data on farm management practices. The lack of data and peer-reviewed science can also mean that the models lag behind the adoption of practices and new technologies that may shift the global average relationships between the quantities of fertilizer applied and the related emissions. Models may also fail to keep pace with the impacts of a changing climate, which could act to push emissions factors and other nitrogen losses upwards.[36]

26. To estimate emissions, the IPCC uses a linear formula based on standard emission factors[d] and the amount of mineral nitrogen fertilizer applied.[37] Inevitably this calculation is a simplification, and may tend to overstate emissions in areas with high but efficient fertilizer use and small nitrogen surpluses, where a greater proportion of the nitrogen than the global average may be likely to be captured by the crop. Conversely, being a global average, it may understate emissions in areas with large nitrogen surpluses.

27. Using this methodology gives annual emissions from current mineral nitrogen fertilizer use of 0.7 Gt CO_2e/year (Table 1), comparable with the emissions from the entire German economy.[38]

Table 1. Global mineral nitrogen fertilizer use and associated greenhouse gas emissions, 2019

Item	Unit	Value
Mineral fertilizer use		
Mineral nitrogen fertilizer use	Mt N	108
Greenhouse gas emissions associated with mineral fertilizer use		
Direct nitrous oxide emissions	Mt CO_2e	461
Indirect nitrous oxide emissions from volatilisation	Mt CO_2e	51
Indirect nitrous oxide emissions from leaching and runoff	Mt CO_2e	122
Carbon dioxide emissions	Mt CO_2	83
Total in-field emissions from fertilizer use	**Mt CO_2e**	**717**

Source: *IFASTAT; Systemiq calculations based on Hergoualc'h et al. (2019), De Klein et al. (2006) and Foster, P. et al. (2021).*

28. Despite the challenges of measuring emissions in the field, there are a number of measures that fertilizer companies and farmers can adopt to start to reduce emissions. Relevant opportunities are discussed in Chapter 2. Following on, Chapter 3 examines the opportunities relating to soil carbon sequestration. Finally, Chapter 4 sets out actions for the fertilizer sector to put emissions on a downward trajectory.

NOTES

a. These are net figures. Gross emissions are higher, with the land use system estimated to remove around 24.2 Gt CO_2e.

Food and Land Use Coalition. (2021). Why Nature? Why Now? www.foodandlandusecoalition.org/wp-content/uploads/2021/10/Why-Nature-PDF-FINAL_compressed.pdf. Accessed 20 July 2022.

b. In this document, “mineral nitrogen fertilizer” is used to refer to all mineral fertilizers that contain nitrogen, including, for example, ammoniated phosphate products.

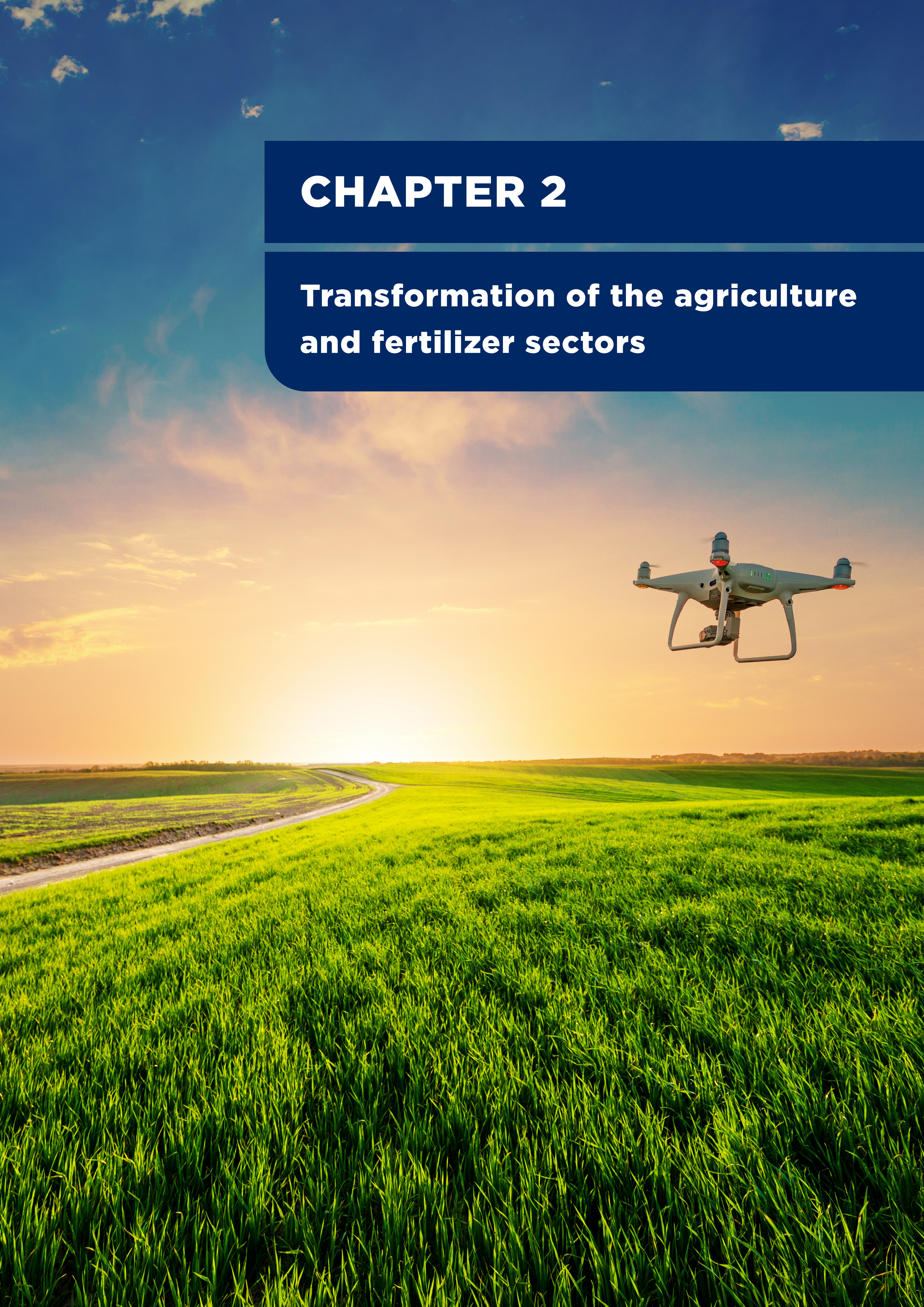
c. Similar emissions occur with the application of organic fertilizers from waste products.

d. The IPCC’s standard tier 1 emissions factors are:

- Direct emissions: 0.01 kg N_2O-N/kg N for general cropping, and 0.004 for flooded rice fields
- Indirect emissions:
  - Share that escapes through volatilization: 0.11 (kg NH_3-N + NO_x-N)/ kg N;
  - Emissions factor for volatilized ammonia and NO_x: 0.01 kg N_2O-N/(kg NH_3-N + NO_x-N volatized);
  - Share that escapes through leaching in wet climates: 0.24 kg N/kg N applied; and
  - Emissions factor following leaching or runoff: 0.011 kg N_2O-N/(kg N leaching/runoff).

CHAPTER 2

Transformation of the agriculture and fertilizer sectors



Emissions from mineral nitrogen fertilizer use can be reduced by around 70% by 2050, at the same time as feeding a growing global population.

Around two thirds of this emissions reduction can be achieved by interventions within the sector's current value chains or business models, mostly from promoting improved nitrogen use efficiency (NUE) but also through developing and promoting increased adoption of enhanced efficiency products and inhibitors.

Further reductions can be achieved through wider changes in the agri-food system where the sector may play more of a supporting role. These include shifts in diets and associated crop diversification, as well as reducing food loss and waste.

There are significant emissions-saving opportunities across regions. In China there remains excessive use of mineral nitrogen fertilizer, especially in smallholder farming systems and fruit and vegetable production. In India, fertilization is too weighted towards nitrogen with insufficient supply of other nutrients. In the United States and Europe there remains scope to push up efficiency through increased adoption of best fertilization practices, as well as additional opportunities from innovative products. In some parts of Africa and Latin America, additional mineral fertilizer will be required. Around the world there are opportunities from wider food system changes to reduce emissions further.

To set an emissions baseline and a science-based reduction target, fertilizer companies need to follow measurement, reporting and verification (MRV) protocols. Care needs to be taken to ensure emissions reductions efforts can be attributable to companies following these, and the sector needs to engage with their further development to reflect the realities of the farming system and to assist farmers in the optimum use of balanced fertilization.

Decarbonizing agriculture will mean substantial changes to the farming systems

1. The agri-food system faces a challenge over the coming 30 years. It needs to increase yields to feed a growing population[39] with nutritious food, while addressing its greenhouse gas emissions. Additionally it needs to maintain or increase soil carbon to sustain soil quality, and free up land for re- and afforestation and restoration of natural habitats. Achieving these goals requires substantial changes to farming worldwide.

2. These changes will build on the significant advances seen in agricultural productivity over the past century. Since 1961, global cereal yields have trebled[40] and the per-capita supply of calories has increased by more than 30%,[41] even as the global population has grown from 3 to nearly 8 billion.

3. Mineral fertilizer has played a key role in this achievement. Crops deplete the naturally occurring nutrients in the soil, and some soils may not naturally contain the nutrients crops require. Some nutrients replenish naturally over time, but not quickly enough to maintain production levels. By applying mineral fertilizers, farmers are able to ensure that crops have access to the nutrients they require, thus boosting yields. With fertilizer, more food can be grown on a fixed amount of land, feeding around half the global population.[42]

4. These gains have not come without a cost. Expansion and intensification of farmland, often with the support of public subsidies focused on production and farm incomes, has in many regions led to the destruction of natural habitats and biodiversity loss, pollution of waterbodies and air, deteriorating soil health and loss of soil carbon. The use of mineral nitrogen fertilizer has led to the release of greenhouse gases, while inefficient use of nitrogen and phosphorus fertilizers has caused air and water quality problems. Conversely, in some regions, intensive farming with a lack of fertilizer (and other technologies) has resulted in soil degradation.

5. Meeting the challenges of the next 30 years will mean expanding and accelerating the shift towards farming practices that restore and maintain soil health and protect natural capital, while increasing yields. In other words, it needs to shift away from inefficient use of inputs, land conversion and degradation of soils.[43]

6. Mineral fertilizer will continue to play a key role. It has ensured that agricultural yields have been able to keep pace with population growth over the past century, and more efficient use will continue to support yield growth in the future. These advances will put the food system on a more sustainable footing, reduce greenhouse gases, and support sequestration of carbon in soils and in forests through avoided land use change.

Improving nitrogen use efficiency (NUE) will be an essential part of efforts to reduce emissions

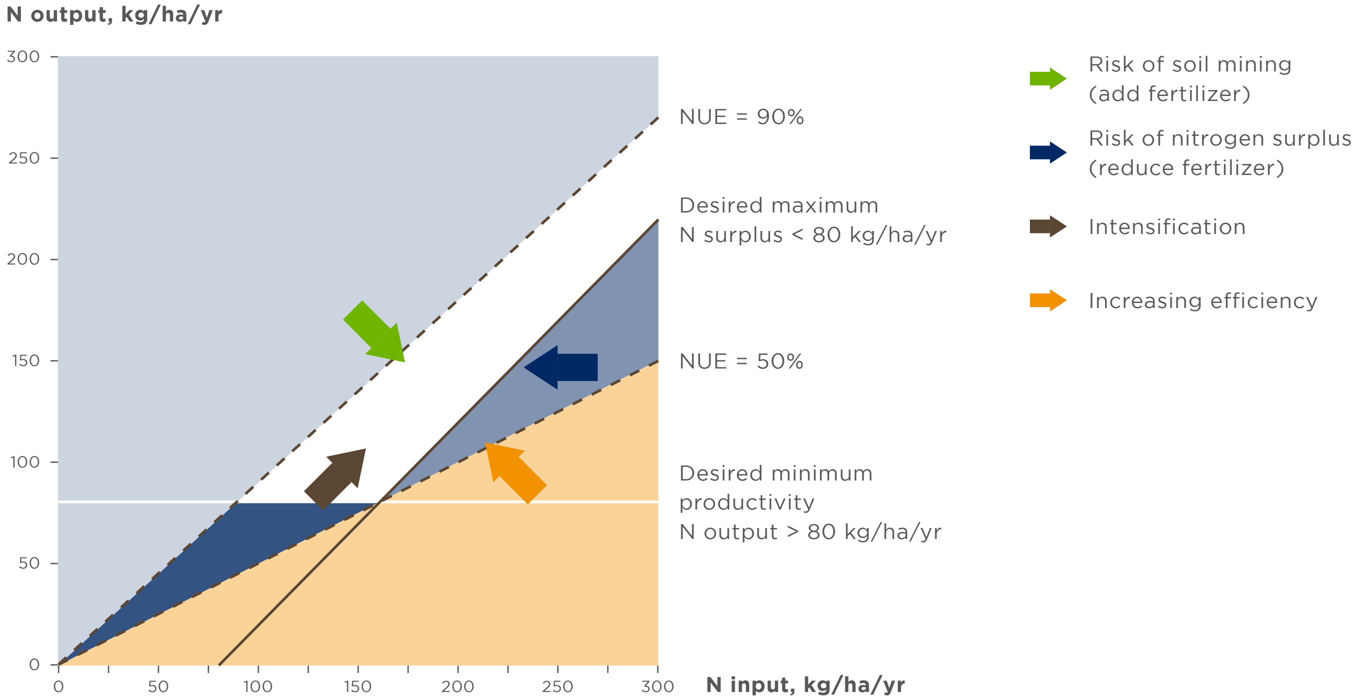
7. The primary measure for reducing emissions from the use of mineral nitrogen fertilizer will be to improve the efficiency of its use while maintaining or increasing yields. Many farmers around the world have adopted many of the best management practices to improve NUE, but in other regions, and on many farms, there is still a lack of access to the knowledge or technology or consistent commercial incentives to be able to follow suit. The outcome is that plants may not have access to all the nutrients they require, while having excessive supplies of others. In the case of nitrogen fertilizer, misapplication can result in periodic nitrogen surpluses, leading to a significant proportion of the nitrogen applied not being captured by the crop. This carries the risk of nitrification, denitrification, volatilization or leaching leading to direct and indirect nitrous oxide emissions.[44] Beyond pollution, this also leads to economic losses for the farmer.

8. NUE is defined as the ratio of the quantity of nitrogen removed from a given area during a harvest and the total amount of nitrogen that enters that area over the season. Nitrogen inputs include mineral and organic fertilizer, biological nitrogen fixation and atmospheric deposition. At an optimal level of NUE, plants are taking up a high proportion of the nitrogen applied to the soil, minimizing the risk of large surpluses and the consequent environmental impacts.

9. There is a delicate balance to strike. If NUE is too low, this suggests there is a large surplus of nitrogen inputs, increasing the risk of nitrous oxide and other nitrogen pollution. If NUE is too high then plants may be taking up more nitrogen than is entering the system, bringing a risk of soil degradation, or "soil mining", with a resulting loss of soil nitrogen and carbon.[45] High NUE may also reduce the protein content of the crop, which may affect its commercial viability especially for feed.

10. The European Nitrogen Expert Panel has developed a framework for NUE, balancing productivity and risks of nitrogen pollution (Figure 1). A realistic ambition would be to improve average global NUE in crop production from around 50% currently to 70% by 2040.

Figure 1. Conceptual framework for nitrogen use efficiency



Conceptual framework of the Nitrogen Use Efficiency (NUE) indicator. The numbers shown are illustrative of an example system and will vary according to context (soil, climate, crop). It illustrates a range of desired NUE between 50% and 90%: values below this range exacerbate nitrogen pollution while values above it risk mining of soil nitrogen stocks. The horizontal line is a desired minimum level of productivity for the example cropping system. The diagonal with shorter dashes represents a limit related to maximum nitrogen surplus to avoid substantial pollution losses. Combined, these criteria identify the most desirable range of outcomes.

Source: *EU Nitrogen Expert Panel (2015)*[46]

11. The fertilizer industry has developed guidance for how to maximize the efficiency of the use of all crop nutrients. This is known as 4R Nutrient Stewardship: applying the right nutrient source, at the right rate, at the right time, in the right place.[47] Following these principles, farmers can maximize the proportion of mineral nitrogen taken up by the plant. This allows farmers to reduce their inputs, or see increased yields for the inputs they do apply.

12. Applying the 4Rs can include use of precision agricultural technologies[a] to better identify plant needs, such as remote sensing monitors, and to place the nutrient as close to the plant as possible when it is most needed, through variable application rate machinery. It will also include ensuring that plants have access to balanced, sufficient supplies of all required nutrients, particularly phosphorus, potassium and sulphur, but also micronutrients – not just nitrogen. Undersupply of any of the macro- or micronutrients required by plants can reduce NUE, and also the efficiency with which other nutrients are absorbed. Among the macronutrients, phosphorus is particularly critical for plants' absorption of nitrogen by improving nodulation and efficiency of bradyrhizobium in legumes[48] and the overall root system development and nitrogen absorption by plants in general. Phosphorus also influences other microorganisms in soil to reduce nitrous oxide emissions from nitrogen application.[49]

13. Applying the 4Rs can be challenging in practice. The precise requirements of any crop will depend on local conditions: the nutrients already present in the soil, the climatic conditions and the varieties of crop being grown. Given the unpredictability and uncertainty inherent in farming, it will never be possible to eliminate nitrogen surpluses entirely and consistently.

14. Furthermore, the choices made within the 4R framework may not be sufficient to reach the socially optimal level of efficiency. Applying the 4Rs where "right" reflects the farmer's immediate business interests will not necessarily align with what is "right" for mitigating environmental risks associated with nitrogen surpluses. Increasing NUE on a farm will come with costs such as new technology, labour inputs and time spent learning new techniques. The gains from reduced inputs may not always make this worthwhile for the farmer. At a society level, however, such emissions reduction measures may still be cheaper than other abatement solutions if taking a broad view across all sources of greenhouse gas emissions, food production and land use impacts.

15. At the same time, maintaining and improving yields is important for ensuring that sufficient nutritious food can be produced without excessive pressure for land conversion. There will also be trade-offs in optimizing NUE and reduced protein content of food, if it means under-fertilization, as was demonstrated in trials in Denmark in the last decade.[50] These factors mean that the yield-maximizing nutrient mix that farmers may be advised to use may differ from the social optimum taking account of all environmental factors. In essence, what is "right" in the 4Rs may vary depending on the context. Efforts to improve understanding of best management practices, innovation to reduce adoption costs, and financial help for farmers to improve the incentive to reduce emissions could all help to shrink this gap.

NUE alone will not be sufficient to decarbonize fertilizer use

16. Improving NUE will go a long way to addressing nitrogen surpluses and so reducing emissions.[51] However, it will not eliminate greenhouse gas emissions from mineral nitrogen fertilizer use entirely. Some mineral nitrogen will always be left in the soil, creating the risk of nitrous oxide generation. Nitrous oxide losses are greatest at times when soils have a high moisture content or high temperature. This means that even if mineral fertilizer application is well managed, there will be instances when nitrous oxide emissions are high.

17. New or improved technologies may help to reduce these losses. Existing technologies such as controlled-release (polymer-coated) fertilizers or nitrification and urease inhibitors have potential to hold mineral nitrogen in the soil for longer or reduce direct and indirect nitrous oxide losses, increasing the chance that plants can make use of nitrogen before nitrification or denitrification can take hold.[52] However, the long-term impacts of such products on the soil are not well understood, and further research is needed to improve their applicability. This will include deepening understanding and addressing any long-term impacts of releasing the polymer coatings into the soil[53] (e.g. by developing biodegradable coatings). Further studies should also seek to determine the extent to which nitrification inhibitors' impact on direct nitrous oxide emissions may be offset by increased ammonia volatilization and indirect nitrous oxide emissions,[54] and nitrification and urease inhibitors' long-term effects on the soil microbiome.[55]

18. Other technologies are further from deployment, but could have longer-term potential. Crop varieties could be developed with improved NUE, or improved carbon fixation through the C4 photosynthesis pathway. Cereal crops could be bred to biologically fix nitrogen. Microorganisms could be added to the soil to fix nitrogen from the air or facilitate plant growth, or biostimulants could be designed to enhance plant metabolism and NUE.

Further changes in the food system would help to reduce emissions further

19. Wider changes to the food system could help to restrain future demand growth for mineral nitrogen fertilizer inputs, and so further mitigate future increases in nitrous oxide emissions:

- Optimizing the use of manure and food waste on soils to provide nitrogen, phosphorous, other nutrients and organic matter. These nutrient sources also carry the risk of nitrous oxide emissions and need to be used as carefully as mineral fertilizers, following 4R Nutrient Stewardship principles, with the additional challenge of uncertain nutrient content.[56] However, as waste products, they already need to be disposed of and their environmental impacts managed, so it is beneficial to use them to support crop nutrition and soil health as part of the wider drive towards a circular economy, particularly when composted.[57] The interactions between organic and mineral sources of crop nutrition have not been extensively investigated in this report;

- Reducing food loss and waste would reduce pressure on cropland; and
- Changing crop rotations to include more biological nitrogen fixation would further reduce the need for mineral nitrogen inputs. Cover crops can further support this, helping further to avoid nitrogen losses and improving soil structure and water retention.[58]

20. However, these changes come with their own constraints: livestock may not be sufficiently geographically close to crop areas for manure to be supplied in a cost-effective way; and changes in human dietary preferences would be required to create sufficient demand for nitrogen-fixing crops. Different crop rotations may also have different nutritional requirements, which could further affect the economics for the farmer. Soya beans require significant potassium inputs, for example.

21. Such shifts are further from fertilizer companies' typical spheres of influence than some of the more direct measures for reducing emissions described in this report. But with supportive government policy and through collaboration with the wider food sector, fertilizer companies may be able to sell products and advice that can support these changes.

A scenario for reducing greenhouse gas emissions from fertilizer use

22. To provide a sense of scale for the potential of the different levers identified, this report presents a top-down scenario for emissions reductions, as well as analysis of six crop systems from regions across the globe.

23. The aim of the top-down scenario is to illustrate the relative potential of the various interventions when applied at scale over the next 30 years. It should not be taken as a forecast or a statement of what should happen, nor an exhaustive list of all interventions. The separate methodology note explains the model in more detail, and the high-level results are presented in Table 1. The ranges shown in Table 1 and Figure 1 are constructed from three sub-scenarios with varying underlying assumptions. This means that the figures shown in the table do not sum.

24. The model first shows that in the absence of improvements in agricultural practices, including fertilization, or dietary changes, projected population growth would require an additional 1.2 billion ha of agricultural land. Productivity growth of 0.8%–1.1% per year, based on long-terms trends and closing yield gaps, including through additional mineral fertilizer application in some regions and improved efficiency elsewhere[b] offsets this somewhat, sparing 220 to 430 million hectares of land from conversion.

25. The model finds that, relative to a business-as-usual 2050 baseline, improving global NUE to an average of 65%–75% through adoption of best practices on farms, including balanced crop nutrition, would allow a reduction in nitrous oxide emissions of 30%–50%, while maintaining food production, saving 220–415 Mt CO_2e per year in 2050, using standard emissions factors.

26. Further emissions savings may be achieved through the wider application of nitrification and urease inhibitors. The modelling assumes application to half of the crop area and half the area fertilized with urea respectively, reducing direct nitrous oxide emissions on those areas by 30%–50% and the fraction of nitrogen from urea that is lost to volatilization by 30%–60%. Reduced nitrogen losses allow further reductions in mineral nitrogen inputs. Overall this measure reduces greenhouse gas emissions by 135–235 Mt CO_2e per year. Nevertheless, making these emissions savings a reality will require a better understanding of these products, their applicability and long-term impacts.

27. Full adoption of these two measures still leaves substantial greenhouse gas emissions of 240–260 Mt CO_2e per year in 2050 from mineral nitrogen fertilizer use. Abating these emissions will require broader changes to farming practices beyond measures directly related to mineral fertilizer use.

28. Changing crop rotations to increase biological nitrogen fixation is one such measure, reducing the need for mineral nitrogen fertilizer and so nitrous oxide emissions from its use. The biologically fixed nitrogen also carries an emissions risk, though the Intergovernmental Panel on Climate Change (IPCC) methodology for estimating nitrous oxide emissions puts these emissions as much smaller than those from mineral fertilizer.[59] The model estimates that increasing the share of legumes in crop rotations from c. 14% up to 20% of global cropland could save a further 25 Mt CO_2e per year in 2050,[c] for example. This would require major dietary shifts by consumers to create a sufficient market for such products, but these crops' higher calorific and protein content would allow some land to be released from production, further reducing mineral nitrogen fertilizer inputs and cutting greenhouse gas emissions 50–65 Mt CO_2e/year in 2050.

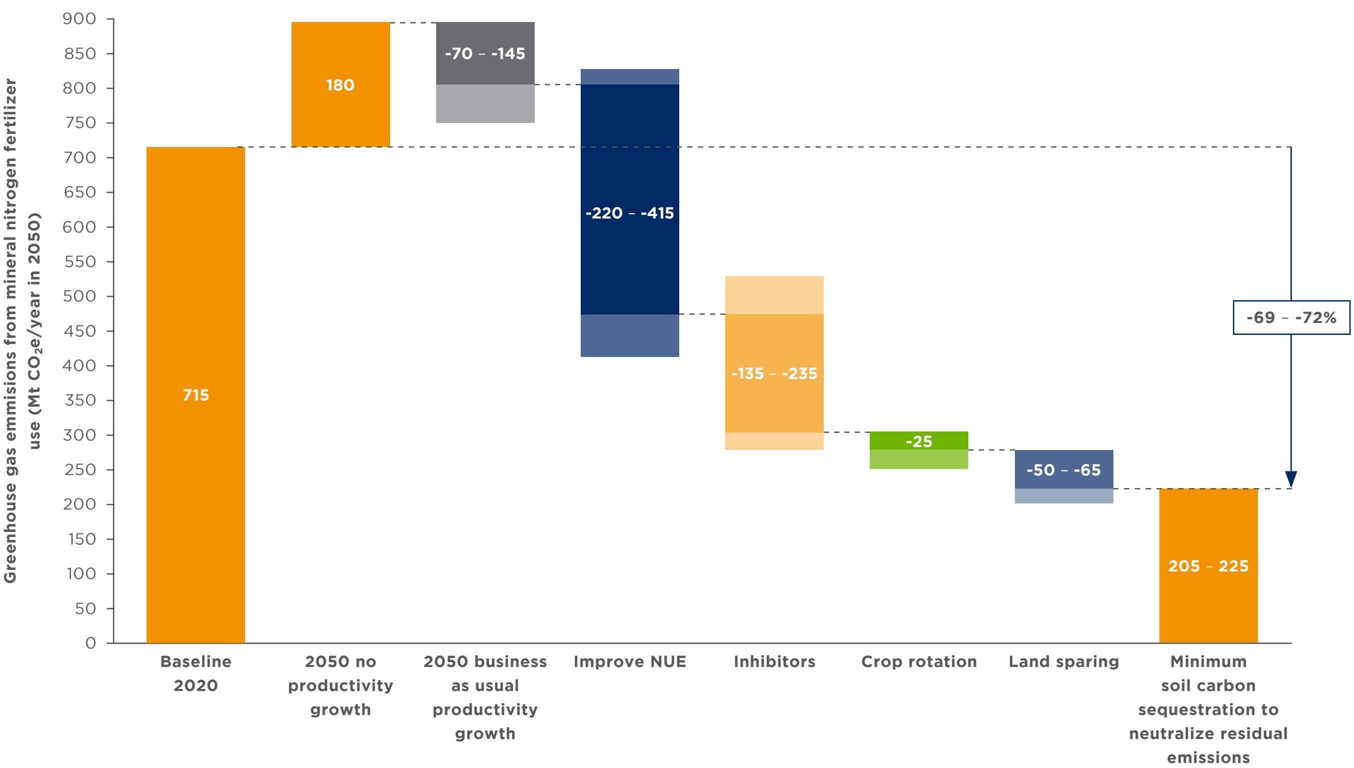
29. Further savings could be realized through joint action across the food system, for example to reduce food loss and waste. This would mean less land and other inputs would be required to deliver the same quantity of nutrients to consumers. Similarly, improved collection and recycling of waste products to soil would reduce the need for mineral nitrogen fertilizer and support soil health, though also carries nitrous oxide emissions risk.

Part of the image collection of the International Rice Research Institute

Table 1. High-level scenario for cumulative emissions reductions in 2050 (figures refer to totals as the measures are applied cumulatively)

	N-fertilizer use	Nitrous oxide emissions	Nitrous oxide emissions (adjusted emissions factors)[d]	Carbon dioxide emissions	NUE	Agricultural land
	Mt N/yr	*Mt CO_2e/yr*	*Mt CO_2e/yr*	*Mt CO_2/yr*	*%*	*million ha*
Baseline	110	635	635	85	48	4 760
2050 no productivity growth	135	790	790	105	48	5 940
2050 with productivity growth	110-125	665-730	605-715	85-95	49-53	5 510-5 720
Improve NUE	60-80	365-470	175-315	50-60	65-75	5 510-5 720
Inhibitors	50-60	240-260	80-115	40-45	76-83	5 510-5 720
Crop rotation	45-55	215-240	70-105	35-40	76-83	5 510-5 720
Land sparing	40	170-190	60-80	30	76-83	4 420-4 550

Figure 2. High level scenario for cumulative emissions reductions



Darker bars show the core scenario, with the lighter shading showing some of the uncertainty around this result. Totals may not sum due to rounding and the way the sub-scenarios are aggregated.

Source: *Systemiq calculations*

Applying these measures in a regional context

30. To better understand the potential impact of these measures at a regional level, this report presents further analysis of six global agricultural regions and opportunities for emissions reductions in these systems. These systems are: wheat-based systems in France; maize–soya bean systems in the United States; maize–soya bean and sugarcane systems in Brazil; rice and maize–wheat systems in China; and rice–wheat systems in northern India.

31. Together these systems account for around 22.4% of the world's total arable land, 32.7% of mineral nitrogen fertilizer use and 30.2% of nitrous oxide emissions from mineral nitrogen fertilizer use.[60] The impact of the measures is summarized in Table 2. The figures here are not comparable with the top-down scenario set out in Table 1, being relative to current practices rather than a business-as-usual trajectory towards 2050.

32. There are significant emissions-saving opportunities across all regions studied. In China there remains excessive use of mineral nitrogen fertilizer, especially in smallholder farming systems and fruit and vegetable production. In India, fertilization is too weighted towards nitrogen with insufficient supply of other nutrients. In the United States and Europe there remains scope to push up efficiency through increased adoption of best fertilization practices, as well as additional opportunities from innovative products. In some parts of Africa and Latin America, additional mineral fertilizer will be required. Around the world there are opportunities from wider food system changes to reduce emissions further.

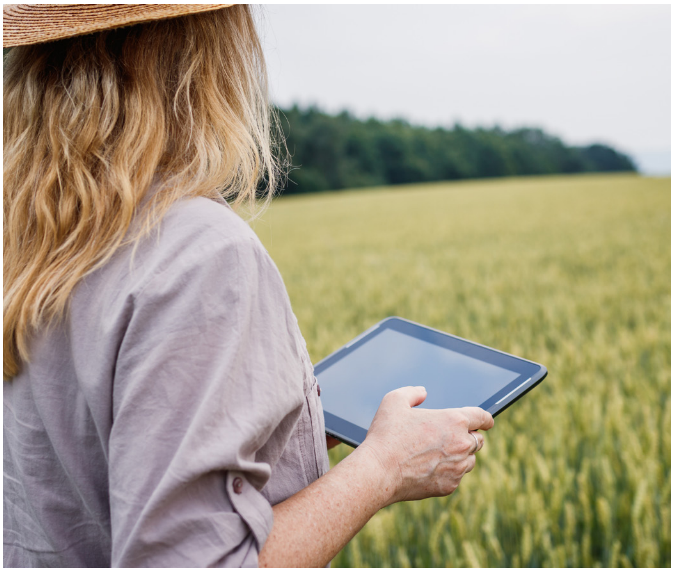


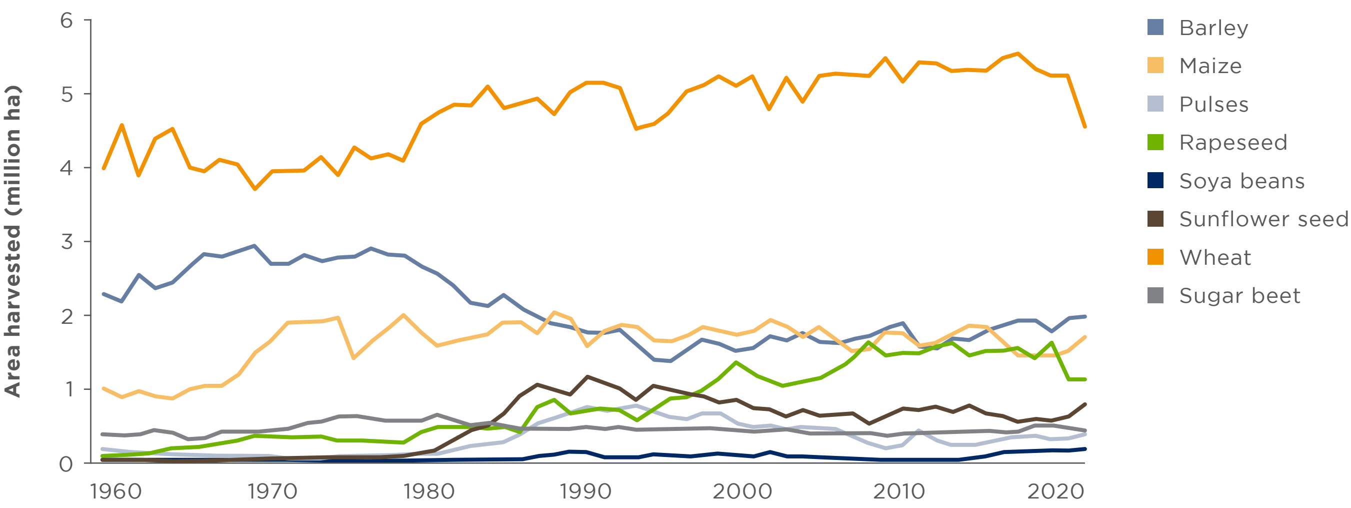
Table 2. Summary of analysis of regional opportunities to reduce greenhouse gas emissions from mineral nitrogen fertilizer use

Intervention	Emissions impact (Mt CO_2e/yr)	Financial impact for the farmer (+ improvement, - loss; €/ha)	Abatement cost (€/t CO_2e)
France			
Wheat-based systems			
Baseline emissions	9.1		
Improving NUE	-1.4	25	-175
Further adoption of nitrification inhibitors	-1.6 – -0.6	-14 – 58	-375 – 217
Improving crop rotations	-1.4 – -1.2	-22 – -33	160 – 269
United States			
Maize-soya bean systems			
Baseline emissions	42.5		
Improving NUE and eliminating excess mineral nitrogen fertilizer application	-11.9 – -6.4	10 – 20	-111 – -100
Extending application of inhibitors	-9.9 – -6.8	-10 – -7	47 – 96
Eliminating monoculture maize	-6.9 – -6.4	-11 – -10	97 – 113
Brazil			
Maize-soya bean systems			
Baseline emissions	3.5		
Improving nitrogen fertilization of double-crop	3.1	-12	N/A
Sugarcane systems			
Baseline emissions	6.5 – 10.8		
Applying inhibitors to sugarcane crop	-5.7 – -1.9	-25	41 – 124
China			
Rice-based systems			
South China double rice crop region			
Baseline emissions	6.4		
Improving NUE through fertilizer-as-a-service	-2.6	281	-883
Yangtze River Basin - Single Rice Crop			
Baseline emissions	10.0		
Enhanced efficiency fertilizers – Urease inhibitors	-0.6	32	-343
Enhanced efficiency fertilizers – Controlled release fertilizers	-0.3	-58	1180
Maize-wheat systems			
Baseline emissions	45.0		
Improving NUE through Increased adoption of precision agriculture	-12.3	-222	317
Improving crop rotations	-9.9 – -4.1	-675	481 – 1160
India			
Rice-wheat systems			
Baseline emissions	12.7		
Improving NUE through mobile technology extension services	-1.9	72	-172
Improving crop rotations	-2.4 – -1.2	-629	569 – 1138

France: Wheat-based systems

33. France is responsible for around 5% of global wheat production.[61] This is primarily concentrated in the north of the country,[62] typically in rotations with secondary crops such as maize, barley or rapeseed.[63] Cultivation of pulses has declined by around 57% since the early 1990s (Figure 3) as crops for animal feed have been displaced by imported soya beans.[64] The analysis here considers wheat as part of this wider crop system.

Figure 3. Crop cultivation in France, selected crops



***Source:** FAOSTAT (2022) "Crops and livestock products: Area harvested"*

34. Fertilization of the wheat crop in France is characterized by relatively high efficiency, with NUE across all cereal crops in France of around 72%,[65] and mineral nitrogen inputs having declined modestly over the last 30 years. Fertilizer doses are routinely split across a season, helping to ensure crops have the nutrients at the point they need them: 79% of the wheat area sees three or more applications of mineral nitrogen fertilizer over a season.[66] This efficiency gain has been achieved without a resulting decline in wheat yields, though yields have been largely stagnant since the early 2000s.[67] Organic fertilizer shows a similar picture, with the total amount of livestock manure applied to soils in France declining 15% since 2000.[68]

35. Despite this high efficiency, there are still gaps in adoption of best practices that could minimize emissions. Survey evidence suggests that many farmers in France overapply mineral nitrogen fertilizer relative to the optimum, citing concerns that the formulas target too low a yield and lack of soil sampling.[69] 98% of the wheat area sees broadcast mineral fertilizer application; almost none of the fertilizer is then incorporated into the soil; and there is no attempt to estimate organic fertilizers' nitrogen content on 28% of the area that is fertilized with organic fertilizer. Moreover, 40% of the wheat area sees nitrogen fertilization based on a farmer's usual dose rather than annual analysis. While application of mineral nitrogen fertilizer is widespread at 98% of the area, other mineral fertilizer nutrients are less widely adopted, potentially due to an expectation that these are fully supplied from organic fertilizer. Only 32% and 18% of the bread wheat area see application of mineral phosphorus and potassium fertilizers, respectively. Considering the wider crop system, only 37% of the soya bean area sees application of mineral potassium fertilizer.[70]

Improving NUE to reduce nitrous oxide emissions

36. This survey evidence suggests that there is scope for further adoption of best practices to improve NUE further. This could include: more consistent soil testing; ensuring the appropriate allocation of other nutrients; incorporating nitrogen from organic fertilizer into calculations; and applying variable rate fertilization on farms to optimize dosage of mineral nitrogen fertilizer in line with the 4Rs guidance.

37. Increasing the precision of the dosage and timing with which mineral nitrogen fertilizer is applied would allow the crop to take up a higher share of the dose. This enables a reduction in the amount of mineral nitrogen applied and a reduced nitrogen surplus, reducing the risk of nitrous oxide emissions.[71]

38. An increase in NUE to 76%[72] would reduce the mineral nitrogen fertilization rate on the cereals and rapeseed area from c. 150 kg N/ha/year to 127 kg N/ha/year. This could save 1.4 Mt CO_2e/year of nitrous oxide emissions and 0.1 Mt CO_2/year of carbon dioxide, a 16% reduction relative to current levels.[73] This is about 0.14 t CO_2e/ha/year across the crop area.[e]

39. Farmers adopting these techniques would see a saving from reduced purchases of mineral nitrogen fertilizer of around €800/year for the average farm, based on a mineral nitrogen fertilizer price of €893/t N,[74] but will also incur costs. Adopting precision agricultural technology, such as variable application rate spreaders, could cost thousands of euros for the average farm, but if done at sufficient scale, should be economical at around €6/ha/year on the affected area,[75] for example by leasing the equipment or buying fertilizer bundled with application services. Further costs could come from increased application of other nutrients to support improved mineral nitrogen fertilizer take-up, or where costs of precision agriculture cannot be adequately shared to achieve economies of scale.

40. Considering only the savings from mineral nitrogen fertilizer (and assuming that precision agriculture techniques can be adopted with economies of scale) still gives a net benefit to the farmer of €25/ha/year and a marginal saving associated with abatement of €175/t CO_2e,[f] meaning it is cheaper than business-as-usual.

Further adoption of inhibitors

41. The model assumes the application of nitrification inhibitors is increased to cover between 60%–80% of the cereal and rapeseed crop area, and urease inhibitors is applied to 13%–17% of the crop area.[g] These are assumed to reduce direct emissions by 24%–36%[76] and indirect emissions from volatilization by 30%–50%.[77] This gives a nitrous oxide saving of 0.9–1.9 Mt CO_2e/year (0.09–0.18 t CO_2e/ha/year). If NUE has already been improved, this saving is reduced to 0.6–1.6 Mt CO_2e/year (0.06–0.15 t CO_2e/ha/year). The likelihood is that the emissions savings would be at the lower end of this range as the emissions reductions estimates are based on figures from some regions with lower NUE than those found in France.

42. Use of nitrification and urease inhibitors keep the mineral nitrogen fertilizer in the soil for longer, increasing the chance that crops can take it up. Some studies suggest this can result in increased crop yields. Wheat yields are estimated to improve by 4.6%–9.6%,[78] which boosts farmer revenues by €28–€79/ha/year, again most likely towards the lower end of the range in France, where yields are already high. With a nitrification inhibitor price of €25/ha–€80/ha[79] and a urease inhibitor price of €14–€33/ha,[80] this gives a net financial impact on the farmer of -€22–€57/ha/year. When NUE has already been optimized, this reduces the need for inhibitors, moving the range of financial impacts to -€14–€58/ha/year if the improved NUE measures have already been applied. However, given the yield impact is likely to be at the lower end of the range, the financial impact is likely to correspondingly be at the lower end of the range of possible impacts.

43. Combining the emissions savings and financial impacts gives a wide range of abatement costs depending on the final price and effectiveness of the products, from a €314/t CO_2e saving to a 239/t CO_2e net cost. If the improved NUE has already been applied, this range shifts to between a €375/t CO_2e saving and a €217/t CO_2e cost.

Improving crop rotations

44. As noted above, legume cultivation – which helps to fix nitrogen in soils – has declined substantially in France over the past 30 years. Reversing this trend and going beyond historical levels to radically increase the amount of biological nitrogen fixation has the potential to substantially reduce greenhouse gas emissions from mineral nitrogen fertilizer use. Currently there is insufficient demand for these products to support increased production, but this could change in the future.

45. Increasing the share of legumes in the rotation to 20% from the current 5%, i.e. to one year in five in the crop rotation, could save 1.6 Mt CO_2e/year of nitrous oxide and 0.1 Mt/year of carbon dioxide relative to 2020 (total 0.17 t CO_2e/ha/year across France). This is 1.2–1.4 Mt CO_2e/year if the higher NUE and inhibitors measures have already been applied (0.12–0.14 t CO_2e/ha/year).[81]

46. Prices and yields for field peas are currently sufficient to support such a change, but this may not be sustained with such a large increase in supply. In particular, these peas are generally produced for fodder, whereas the dietary changes required to support such a change would most likely require different crops. Current soya bean prices and yields would not make the change in crop rotations a profitable change.

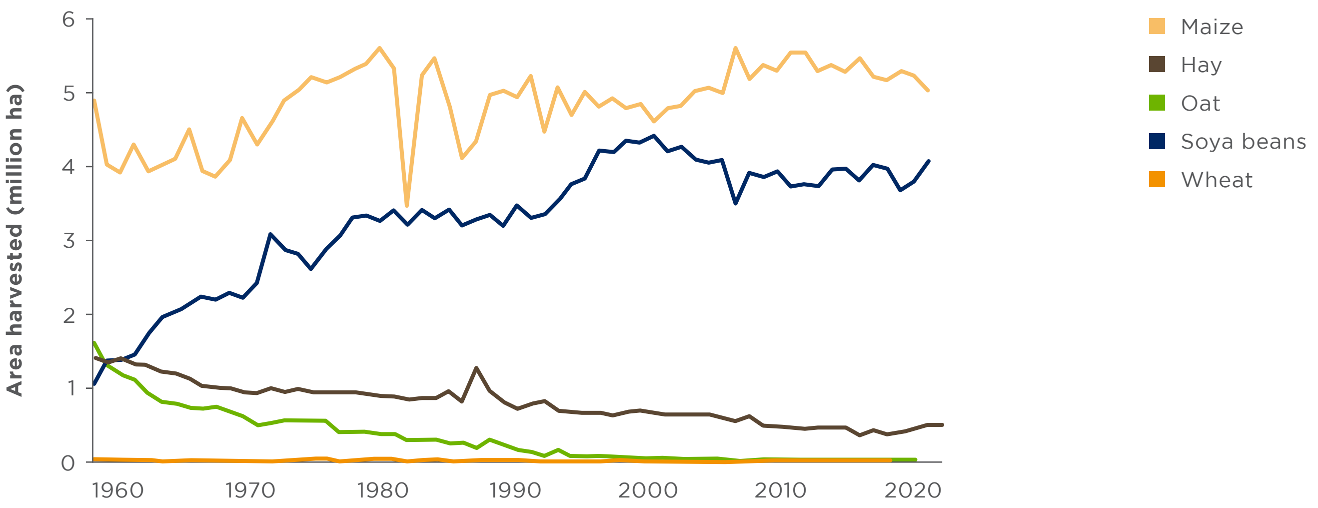
47. If the current mix of legume crops is maintained as their crop area is expanded, farmers would see a net revenue loss of €42/ha/year, which is not entirely offset by the reduction in mineral nitrogen fertilizer costs of €24/ha/year, or €24–€28/ha/year if the NUE and inhibitor measures have been applied. Further costs could come from any required additional nutrients to support such crops.

48. Taking the average producer price in 2015–2019 and focusing on the foregone revenue and mineral nitrogen fertilizer costs gives a net loss of €18/ha/year or €18–€21/ha/year if the NUE and inhibitor measures are applied. That gives an abatement cost of €106/t CO_2e, or €143–€154/t CO_2e if emissions have already been reduced through the NUE and inhibitors measures. In this context just a 2% increase in prices would be enough to break even.

US: Maize–soya bean systems

49. The United States is responsible for around a third of the world's maize and soya bean production,[82] with production concentrated in the Midwest region.[83]

Figure 4. Crop cultivation in Iowa, selected crops



Source: *USDA/NASS Quick Stats (2022)*

50. While the region has long been a centre for maize production, soya bean cultivation grew strongly in the second half of the 20th century, squeezing out other secondary crops such as oats and wheat (Figure 4).

51. At the same time, the United States has achieved high NUE (71.6% in 2014),[84] with biological nitrogen fixation from the soya bean crop supporting mineral nitrogen fertilization at an average rate in Iowa of 162 kg N/ha/yr. This has increased from an average 148 kg N/ha/yr between 2000 and 2010.[85] Reasonable efforts are also made towards ensuring balanced nutrition, with 85% of the maize area being tested for phosphorus fertilization.[86] Nitrogen mineral fertilization is associated with annual emissions across the US maize–soya bean crop system of around 42 Mt CO_2e of nitrous oxide and 3 Mt CO_2 of carbon dioxide.[87]

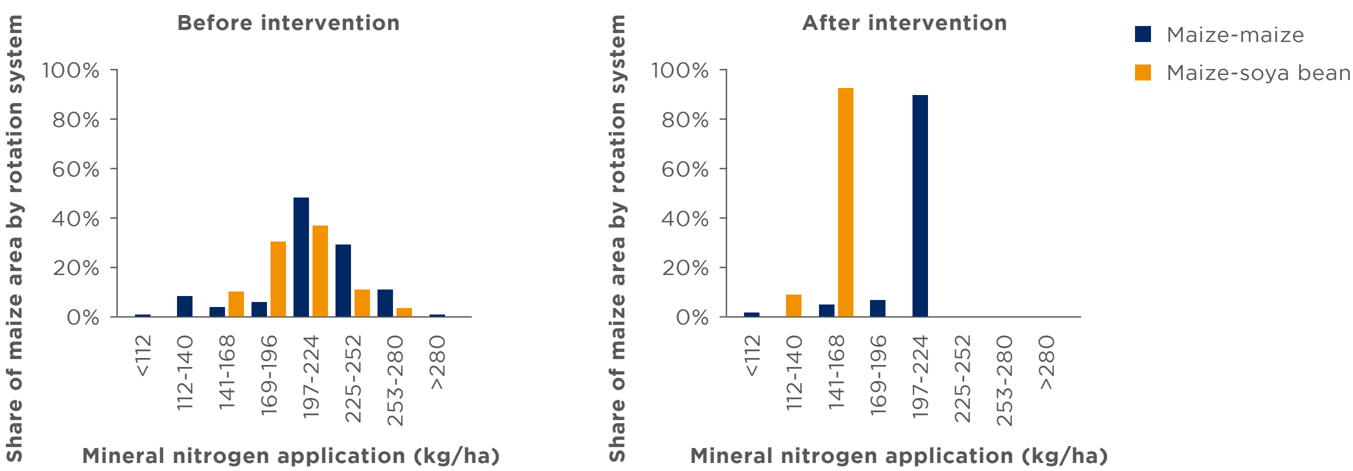
52. There should be scope to improve NUE further. In Iowa – taking the state as a case study – there is a predomination of single applications of mineral nitrogen fertilizer, rather than split application that would allow more precise dosage aligned to when the maize crop most needs it. The situation is improving, however, with an average 1.7 applications per year in 2010–2018 for maize in Iowa, compared with 1.4 applications in 2000–2005.[88] The share of the maize area in Iowa fertilized with a spring/in-season split doubled to 20% between 2017 and 2019. Around 50% of fields see a single spring fertilizer application before planting, with around 30% seeing fertilization in the autumn, mostly with the application of nitrification inhibitors, and the remaining 20% have a spring–in season split.[89]

Improving NUE and eliminating excess mineral nitrogen fertilizer application

53. The Iowa Nutrient Reduction Strategy identifies eliminating excess mineral nitrogen fertilizer application above the maximum return to nitrogen value as a key measure to addressing nitrogen pollution.[90] Mineral nitrogen application to maize in Iowa is an average 162–201 kg/ha,[91] but within this average about 72% of fields see applications above the maximum return to nitrogen values. The excess is 149 kg N/ha for maize–soya bean and 213 kg N/ha for maize–maize (Figure 5).[92]

54. Eliminating this surplus would reduce mineral nitrogen fertilizer inputs by 18%. This would reduce nitrous oxide emissions from the maize–soya bean system in Iowa by 0.9–1.6 Mt CO_2e/year, and carbon dioxide by 0.1 Mt/year. Scaling these results up to all US maize production gives a total emissions saving of 6.4–11.9 Mt CO_2e/year.

Figure 5. Distribution of mineral fertilizer application to maize in Iowa, 2019



Source: *Iowa State University (2021)[94] and Systemiq calculations.*

55. This change could have a small yield impact of approximately -1%,[93] costing around €8/ha/year.[h] This is offset by reductions in fertilizer costs of around €13–€23/ha/year. There may also be costs to adopting more precise fertilization practices. If done at scale – which is likely to be feasible for the average farmer in Iowa with 146 ha[94] of land – there could be capital costs of around €5/ha/year, but also labour savings of €9/ha/year.[95] This gives a net saving for farmers of €10–€20/ha/year, with a saving associated with abatement of €100–€111/t CO_2e.

Extending application of inhibitors

56. Around 28% of the maize area in Iowa sees nitrification inhibitor application.[96] Assuming that nitrification inhibitors reduce nitrous oxide emissions by 42%–64%,[97] increasing their application to 80% of the maize area could reduce nitrous oxide emissions by between 1.2 and 1.8 Mt CO_2e/year. This is 8.3–12.0 Mt CO_2e/year if the estimate is scaled up to all US maize production. If the measures to reduce excess nitrogen have already been applied, these figures are 1.0–1.4 Mt CO_2e/year for Iowa and 6.8–9.9 Mt CO_2e/year for the United States.

57. This is a relatively low-cost measure for farmers, costing around €7–€12/ha/year when spread across the whole crop area.[i] This gives an abatement cost of €39–€96/t CO_2e, or €47–€96/t CO_2e if the measures to eliminate excess mineral nitrogen fertilizer have already been applied.

Eliminating maize-maize rotations

58. Around a quarter of the maize area is cultivated on a maize–maize basis rather than in rotation with soya beans.[98] This misses opportunities for biological nitrogen fixation, as well as the wider benefits to soil health of rotating crops.

59. Switching all maize–maize to maize–soya bean rotation could have a net emissions saving of 1.1 Mt CO_2e/year of nitrous oxide and 0.1 Mt/year of carbon dioxide relative to current practice, or 0.9–1.0 Mt CO_2e/year if the excess nitrogen application has already been eliminated and inhibitors have been applied. If scaled up to all US maize production, this measure would save 7.6 Mt CO_2e/year of nitrous oxide and 0.5 Mt/year carbon dioxide, or total 6.4–6.9 Mt CO_2e/year if the other measures have been applied.

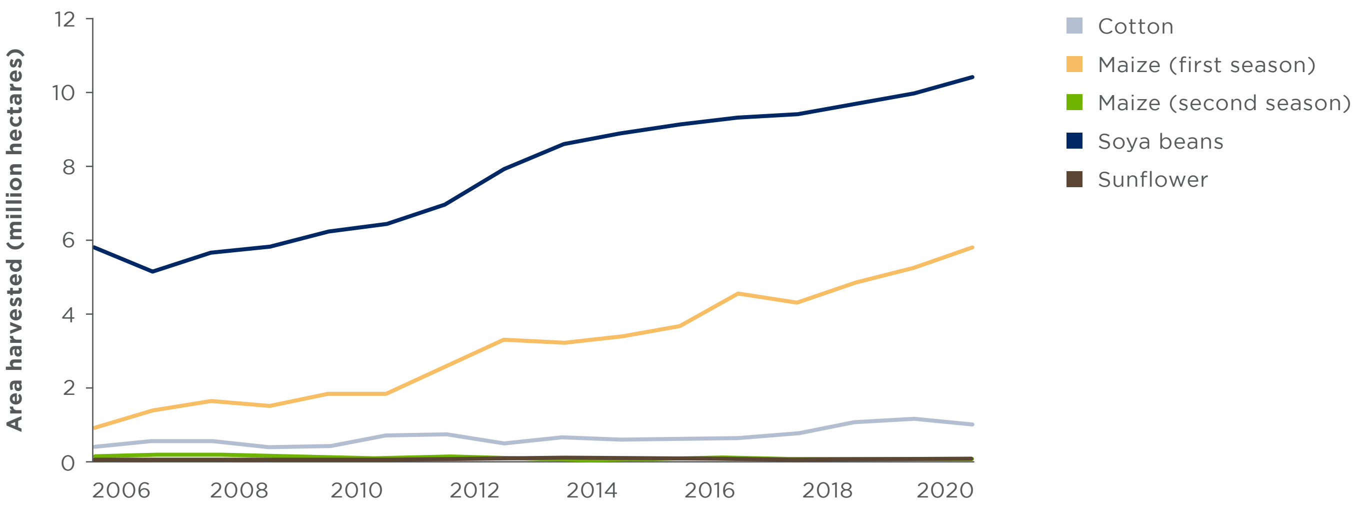
60. The financial impact of such a move is likely to be negative for the farmer. The net impact on revenue of switching some maize production to soya bean is a reduction of €30/ha/year, which more than offsets the approximately €17/ha/year saving from spending on mineral nitrogen fertilizer. This gives a net cost of €13/ha/year, or €9–€10/ha/year if the other measures have already been applied. That leads to an abatement cost of €104/t CO_2e, or €87–€102/t CO_2e if the other measures have also been applied.

61. This costing is likely to be an underestimate, as it is based on average yields, whereas it is the most productive land that is likely to be used for maize monoculture. It also does not take account of additional nutrients that the soya bean crop may require. Finally, this would be a 16% step up in soya bean production. Wider changes in the food system such as changes in diets would be required to create a sufficient market for such additional production.

Brazil: Maize-soya bean and sugarcane

62. Maize and soya bean cultivation is widespread across Brazil, but in the state of Mato Grosso, the crops are farmed most intensively, with double cropping becoming the predominant system.[99] Soya beans are planted in October and harvested in February, with maize planted immediately after the soya bean harvest, to then be harvested in July.[100] Shifting to this system has allowed a large expansion of soya bean and maize production in the state (Figure 6). NUE in the region is very high, potentially pointing to mining of the soil's nitrogen stocks.[101] Despite short-term gains this trend could hold back the long-term productivity of the system.

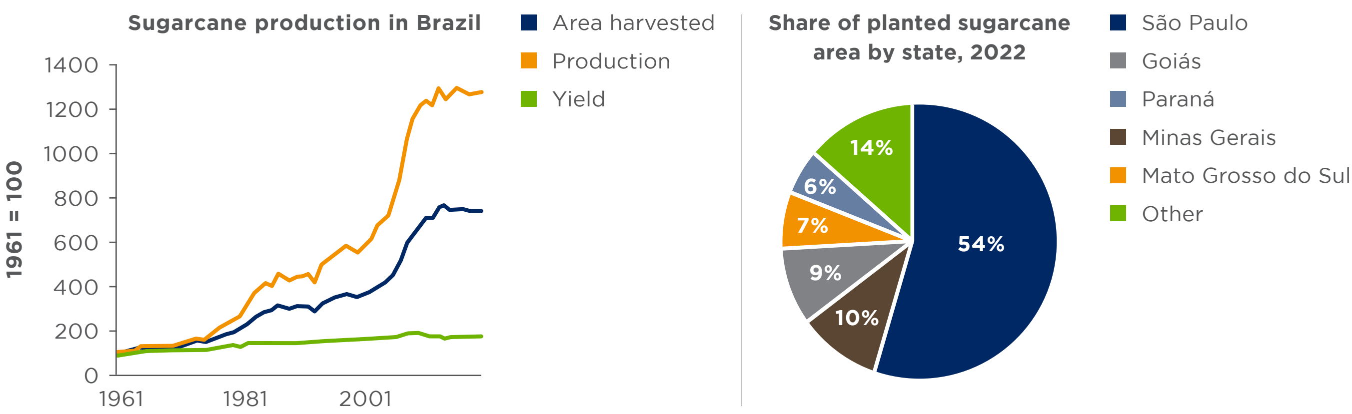
Figure 6. Crop cultivation in Mato Grosso



Source: *Brazilian Institute of Geography and Statistics (IBGE)*[102]

63. Sugarcane production is concentrated in Brazil's central-west and south-east regions,[103] particularly São Paulo state, which accounts for 54% of the planted area. Production first took off in the 1970s, and then accelerated in the 2000s, responding to demand for ethanol for biofuels,[104] while yields have been stagnant (Figure 7). Sugarcane production is characterized by high nitrous oxide emissions resulting from the application of mineral nitrogen fertilizer with vinasse, a waste product from ethanol production, which induces certain physicochemical changes in the microorganisms in the soil.[105]

Figure 7. Sugarcane production in Brazil



Source: *IBGE, FAOSTAT*[106]

Improving nitrogen fertilization of double cropped maize–soya bean

64. NUE in the double crop region of Mato Grosso is around 90%. The figure is likely to be suggestive of a long-term loss of soil fertility over time.[107] This could undermine productivity in the long run and so could create pressure for deforestation as farmers look to maintain output.

65. Increasing application of mineral nitrogen fertilizer could support higher maize yields and longer-term sustainability of production in the region. An estimate of increasing mineral nitrogen application to double-cropped maize from around 63 kg N/ha/year to 119 kg N/ha/year, combined with a 10% increase in maize yields,[109] could bring NUE down to a sustainable level of around 75%, assuming yield is proportionate to nitrogen uptake.[110] However, the additional yield is not currently sufficient to offset the cost of the additional fertilizer, with a revenue gain of €27/ha, compared with the additional fertilizer cost of €39/ha.[112] In the longer term, soil mining would start to undermine productivity, thereby improving the potential financial impact of the change.

66. Increasing mineral nitrogen fertilizer application increases the risk of nitrous oxide emissions. According to the IPCC methodology, it could lead to an increase in emissions in the Mato Grosso region of 2.7 Mt CO_2e of nitrous oxide and 0.4 Mt of carbon dioxide. However, the nitrous oxide impact is likely to be lower than estimated here given the high uptake and low current nitrogen surpluses.[111] Furthermore, the increased yield could reduce pressure for deforestation, with a carbon opportunity cost saving from potential avoided land use change of 6.3 Mt CO_2e.[112]

Applying inhibitors to sugarcane production

67. The application of vinasse alongside mineral nitrogen fertilizer is associated with higher nitrous oxide than mineral nitrogen fertilizer alone.[113] In a scenario where vinasse accounts for 1.5%–2.85% of the mix, total greenhouse gas emissions from fertilization of sugarcane in Brazil would be 6.5–10.8 Mt CO_2e.[114]

68. NUE is relatively low in the sugarcane region,[115] but there is not significant scope to improve it through adjustment of mineral nitrogen fertilizer application given the majority of nitrogen for the crop comes from other sources, including some limited biological nitrogen fixation.[116] Nitrification inhibitors may help to reduce these excess emissions by 50%–80%.[117] If applied to 80% of the sugarcane area, this could reduce nitrous oxide emissions by 1.9–5.7 Mt CO_2e. This would come at a cost of €25/ha,[118] giving an abatement cost of €41–€124/t CO_2e.

China: Agriculture and fertilizer use

69. In recent decades, China has transformed its agricultural sector. This has led to significant improvements in farming outcomes and livelihoods. Part of this has been driven by a large increase in mineral fertilizer inputs. This has improved yields, but nitrogen and other mineral fertilizers are now applied at some of the highest per-hectare rates in the world, and growth in mineral inputs has outpaced yield growth.[119] As a result, China has one of the lowest NUEs globally[120] at 47% in 2017.[121] Nevertheless, average NUE for cropland in China has been improving since the mid-2010s, according to statistics released by the national government.

70. In 2015, China's Ministry of Agriculture adopted a policy of zero growth in the use of mineral fertilizers by 2020. This initially targeted air pollution from volatile ammonia and water eutrophication in the case of nitrogen-based fertilizers, rather than atmospheric pollution through greenhouse gases. Average NUE for cropland in China has been improving since then, according to government statistics. In fact, China has been on a downward trajectory of nitrogen fertilizer use since 2013, and levels of mineral nitrogen usage are now at levels last seen in 2004.[122]

71. These reductions have been achieved without disrupting the longer-term goal of achieving food security through self-sufficiency for the main staple crops through continued crop yield growth, though for now the country is still a significant importer of food.[123] However, China still uses 24.1 Mt of mineral nitrogen fertilizer annually, the most of any country in the world, due to its high population and need to derive high yields from relatively small arable cropland.

72. Domestic mineral fertilizer production is also being reorientated towards higher-quality, higher-yielding products, in line with the zero-growth policy. Locally produced ammonium bicarbonate was traditionally the most common nitrogen fertilizer. This has particularly low NUE and high losses to ammonia volatilization.Urea has mostly replaced this in recent decades as the most-used nitrogen fertilizer in the country, at 34% of total nitrogen fertilizer, again mostly sourced from domestic production.[124] The higher efficiency of urea versus ammonium bicarbonate has contributed to improving NUE at national level. More recently there is also a shift to more compound fertilizers, or value-added urea.[125]

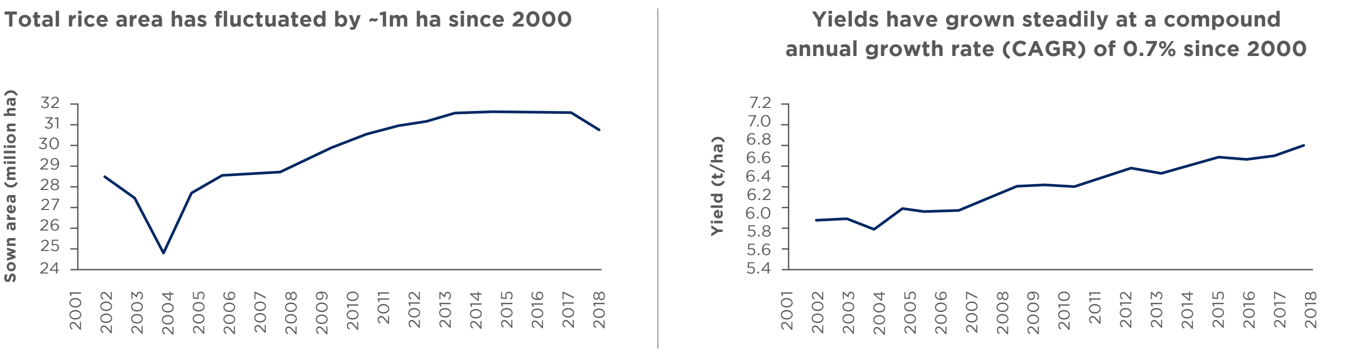
73. Farming in China across nearly all crops remains dominated by a smallholder farming system. The average farm size is estimated to be between 0.4–0.6 ha.[126] At the same time, for many years there has been a drain on labour availability in rural China, despite the stringency of China's *Hukuo* (household register) system that limits internal economic migrants from agricultural backgrounds accessing public services and social benefits in urban areas. This trend had been slowing before the COVID-19 pandemic and now reverse migration to rural areas is starting to grow.[127] But the past migration has meant agricultural output from smallholder farms has relied on an ageing workforce or those with multiple responsibilities, such as raising children or other supplementary employment.[128] Labour shortage in rural areas contributes to inefficient fertilizer management practices.

74. The labour shortage in rural areas and dominance of smallholder farms contributes to inefficient fertilizer and other input management practices. These farmers generally have part-time jobs in urban areas compared with professional farmers in large-scale farms and therefore are less dependent on income from cropland and less sensitive to fertilizer price, leading to more excessive use proportionally to the amount of land farmed.[129] On average, a 1% increase in farm size in China is associated with a 0.3% decrease in fertilizer use, with a negligible impact on yields,[130] though this initial benefit eventually fades and reverses as farms grow larger and become more complex to manage.[131]

China: Double rice cropping in South China and single rice cropping in Yangtze River Basin

75. The majority of rice production in China can be found in two major growing regions defined by the number of rotations in a year. First, a double rice crop, mostly grown in the South China coastal region, with an early crop from early April to July followed by a late crop in July to October. Second, a single rice crop, primarily in the Yangtze River basin region, grown from late May to late September and rotated with other upland crops. Over the past 30 years, rice cultivation in north-eastern China, particularly in the province of Heilongjiang, has also expanded in size and significance – in response to the national priority to reach self-sufficiency in grain production.[132]

Figure 8. Rice cultivation in China



Source: *China National Bureau of Statistics*[133]

76. The single rice crop growing area covers nearly four times that of double rice crop regions, and is also much more productive, with average yields of 1.5 t/ha per harvest higher than double-cropping regions.[134]

77. There are also operational differences in how farming operates in these two regions. There is a much higher level of mechanized planting in the single rice crop region, and approaches to irrigation management are also different.[135] As such, the two systems are analysed as two distinct sub-systems.

78. The emissions profile of rice is different from other grain crops. Nitrous oxide emissions from fertilizer use are a much smaller component of the total footprint, with methane emissions produced from anaerobic conditions of paddy field flooding and emissions from straw burning being the largest and second-largest greenhouse gas components of rice production in China.[136]

79. This is reflected in the difference in calculation of emissions factors in the IPCC methodology for nitrous oxide emissions from mineral nitrogen fertilizer and other nitrogen amendments in rice compared with other crops. On the one hand, Tier 1 and Tier 2 emissions factors for nitrous oxide emissions from mineral nitrogen fertilizer are smaller for flooded rice fields than other crops.[137] On the other hand, emissions calculations for land cultivated for rice include an additional step in order to include methane.

80. That said, the impact of excess mineral nitrogen fertilization of rice is consistent with other crops and, beyond environmental concerns, fertilization beyond optimum levels may be detrimental to rice yields by increasing susceptibility to lodging (falling over).[138]

81. Rice field emissions beyond nitrous oxide are not within the scope of this study, as they are not released in the use-phase of a fertilizer product. Nevertheless, targeting only nitrous oxide emissions in rice cultivation may exacerbate other emissions. This is particularly the case with methane where, broadly, the anaerobic conditions in flooded paddy fields inhibit nitrous oxide emissions but enhance conditions for methane.

82. Ultimately, fertilizer companies should practise good corporate citizenship in this space to ensure initiatives to reduce their own Scope 3 emissions have an overall net reduction in farmers' direct emissions across all gases. Fertilizer companies may need to work with other agri-input companies to influence wider practices in land preparation, seeds and planting, and weed and disease management.

Improving NUE through fertilizer-as-a-service

83. Best practice and site-specific nutrient management following the 4Rs principles[139] can improve yield and NUE in rice and other crops. However, other than reducing input costs, there may be little incentive to limit overuse of nitrogen fertilizer by applying the right form of nitrogen at the right time. Often, these embedded practices are seen as a substitute for additional labour or other inputs for absent migrant farmers.[140]

84. Changing crop nutrition to a fertilizer-as-a-service model could be a way to address this. In this model a fertilizer provider – either a manufacturer directly or partnering with a downstream distribution partner – would move away from solely providing mineral fertilizer that may or may not be complemented with agronomic advice. These companies would instead move to a model where they manage the entire fertilization process, using appropriate machinery. The farmer would make payment for delivery of the service rather than for the fertilizer itself. This could be linked to an outcome-based contract centred on yield improvement to ensure mutual benefit, effectively sharing profit between the two parties.

85. The South China double crop regions have traditionally had the lowest level of mechanization of rice cultivation in China, and farms generally use small-scale machinery for land management and harvesting.[141] Mechanized fertilization is less common. This means there would be less sunk cost in capital equipment for farmers adopting this fertilizer service provision compared with other regions.

86. Shifting the relationship between farmer and input provider in this way may increase mechanized application and create positive outcomes for all parties. For farmers short on labour and time, it can help them to implement best practice nutrient management. This enables the farmer to spend less time in the field,[142] or to focus on other labour-intensive practices that can also influence both yield and emissions, such as irrigation management.

87. For the fertilizer provider, shifting from product to service can help maintain profitability in the face of reduced fertilizer use, while simultaneously reducing the company's Scope 3 emissions. There is already precedent in China for the relationship between agricultural input providers and farmers to move from product transaction to a service-orientated relationship that is seeing beneficial outcomes for both farmer and input company.[143] However, as of yet there are no fully functioning fertilizer-as-a-service models deployed at scale, so further research and development would be needed in this space to make it a reality.

88. Applying best practices could reduce mineral nitrogen application by 25% from a baseline of 165 kg/ha for early rice and 177 kg/ha for late rice.[144] It would require more fertilizer applications and a change in the ratio of nitrogen content applied at each growing stage. Best management practices are also assumed to include application of other nutrients at optimum rates.

89. With 80% of farms reducing their nitrogen application rate by up to 25% across the double rice crop region, this intervention could reduce emissions by 2.6 Mt CO_2e annually relative to 2020 levels. If annual yield improvements reached 5%, farmers would see a revenue increase of €281/ha. This forms the maximum price a provider could charge for the fertilizer service, including the cost of fertilizer product. This equates to an opportunity for the farmer or fertilizer company of €883/t CO_2e abated.

Reducing emissions through enhanced efficiency products

90. Urea remains a major source of mineral nitrogen fertilizer in China, representing around a third of all mineral nitrogen consumed.[145]

91. Excessively rapid hydrolysis of urea can result in volatile ammonia rather than ammonium. Only a limited amount of ammonia can be used by plants, so most is lost to the atmosphere, leading to local air pollution and, indirectly, to nitrous oxide emissions. These losses, and losses associated with wider inefficient use, can be partially addressed through the use of urease inhibitors and controlled-release fertilizers (CRFs).[146]

92. Urease inhibitors are widely available and cost effective, but CRFs have a large price premium, so have had limited uptake. Globally, in 2005, nitrification and urease inhibitors carried a 30%–60% price premium over NPK blends, whereas controlled-release coated fertilizers were between 800% and 1,200% more expensive.[147] In 2017, this premium on polymer-based CRFs had declined to around 240%.[148] In China, in 2020, the price differential was 130%–260% compared to soluble urea.[149] Blends of conventional urea and polymer-coated urea can also help to mitigate the price premium.

93. Polymer-coated CRFs also release microplastics into the soil, and there are increasing signs of potential regulatory action to restrict their use.[150] Some polymer coatings that are claimed as biodegradable are now available, but these are mostly for specialist use and not prevalent in row crop cultivation.[151] However, microplastics leakage of polymers used to coat CRFs are unlikely to be a barrier to adoption by most farmers.

94. Though not modelled in this case study, there is also evidence to suggest that combining urease and nitrification inhibitors can have a synergistic effect on reducing nitrogen losses.[152] This may be another strategy in flooded rice fields where the efficacy of individual inhibitors may be challenged by the soil moisture levels and pH.

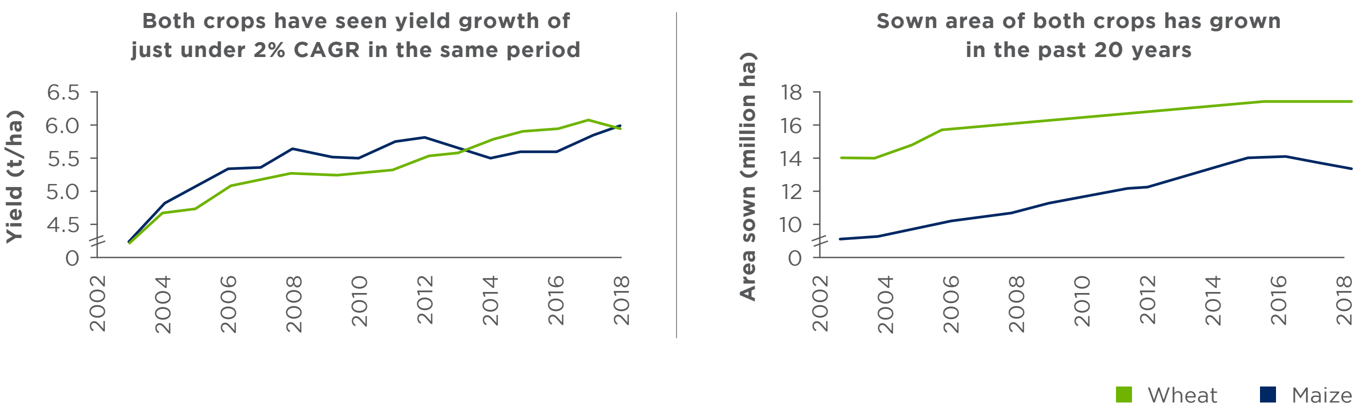
95. Noting these caveats, the model suggests that application of urease inhibitors to 80% of the single rice crop area, with controlled-release mineral nitrogen fertilizers used on the remaining 20%, could reduce emissions by almost 1 Mt CO_2e/yr. Within that figure, 0.65 Mt CO_2e is from the urease inhibitors and the remainder from the CRFs. This is assuming urease inhibitors reduce nitrous oxide emissions from ammonia volatilization by 50% and CRFs allow a net reduction in mineral nitrogen fertilizer application of 20%, reflecting such products' greater efficiency.

96. If these changes result in annual yield improvements of 2% and 2.5% respectively for each technology, farmers would see a net benefit of €32/ha for urease inhibitors and a net cost of €58/ha for CRFs. This equates to an opportunity of €343/t CO_2e mitigated from urease inhibitors and a cost of €1,180/t CO_2e mitigated from controlled-release inhibitors.

China: Maize–wheat in the North China Plain

97. The North China Plain, taken in this study to cover the provinces of Beijing, Tianjin, Hebei, Jiangsu, Anhui, Shandong and Henan, is another important agricultural region in China. It represents more than 75% of China's winter wheat area and more than 30% of maize,[153] with similar levels for crop output.[154] Wheat is typically grown during the winter season from September to June, with maize grown over the summer from June to October.[155] Winter wheat–maize is the most common rotation in the region, found on 28% of farms, with the next most common rotation being continuous spring maize found on 19% of farms.[156]

Figure 9. Maize–wheat cultivation in China



Source: *China National Bureau of Statistics*[157]

98. Excessive use of nitrogen fertilizer has been a long-term issue in the region, though this has mainly been identified as localized ammonia environmental pollution.[158] Along with vegetables, maize and wheat account for 80% of nitrogen losses in the North China Plain.[159] Average nitrogen fertilization rates are 254 kg/ha for winter wheat and 214 kg/ha for maize.

Improving NUE through increased adoption of precision agriculture technologies

99. Increased adoption of precision agriculture technologies could improve NUE and sustainability in the region.[160] These can be used to implement best management fertilization practices following the 4Rs, primarily by applying fertilizer at the right time and right place to ensure nutrients are delivered when crops most need them and at a location where they are most required by plants.

100. Nitrogen fertilization rates optimized for maximum yield (>97% of maximum yield), economic impact and NUE to achieve a favourable nitrogen balance have been identified at 202 kg/ha for wheat and 179 kg/ha for maize in the North China Plain.[161] These represent a 20%–30% reduction of current fertilization practices in the region.

101. Assuming adoption of precision agriculture on half of the sown area of winter wheat to achieve these fertilization rates, it could save 9.7 Mt CO_2e/yr in nitrous oxide emissions and 2.6 Mt/yr in carbon dioxide. That is a 27% saving compared with current levels.

102. With an increase of 3% in annual yield output, farmers could expect to see a revenue benefit of €117/ha and savings from reduced fertilizer use of €172/ha. However, if individual farmers were required to make the capital investment towards machinery, it would offset these revenue gains and input cost savings, leaving farmers worse off by €222/ha. Alternatively, this investment could be made by a service provider to reduce the financial burden on farmers directly. Overall, this gives a marginal abatement cost of €317/t CO_2e emissions reduced.

Improving crop rotations

103. The most recent five-year plan in China called for a 40% increase in soya bean production by the end of 2025, with 85% of consumption currently coming from imports.[162] Soya beans in the North China Plain only account for 3% of cultivated land,[163] with a double crop of winter wheat and soya beans being the most common annual rotation that includes soya.[164] This wheat-soya bean double crop is also grown in alternation with maize in a two-year cycle.[165]

104. Beyond domestic self-sufficiency (food import reduction) goals, increasing the cultivation of soya beans in China has the potential to reduce greenhouse gas emissions from mineral fertilizer use. Increasing the cultivated area of soya beans to 15% in the North China Plain has potential to save 4.9–11.7 Mt CO_2e/yr, or 4.1–9.9 Mt CO_2e/yr if other NUE measures have already been applied. This assumes optimum fertilization of soya beans still requires some nitrogen application to reach desired yield, at 33 kg N/

ha, balanced with other key nutrients including phosphate and potassium.[166] Application of rhizobia with soya bean seed may also be appropriate to reduce nitrogen application rate.

105. Current yields of soya beans in the North China Plain are on average 1.5–2 t/ha.[167] This is well below benchmarks for key global producer regions of more than 3 t/ha.[168] Even with an increase in average yield to 2.1 t/ha, decreased input costs from reduce mineral nitrogen fertilizer inputs are not sufficient to offset the revenue losses from the lost maize crop, given long-term average domestic prices for soya beans and in the absence of government incentives. This leaves farmers' financial positions at a net negative of €657/ha, or €675/ha if NUE measures have already been applied. This gives a marginal abatement cost of €408–€983/t CO_2e, or €481–€1,160/t CO_2e after other measures have been applied.

India: Rice-wheat in Punjab & Haryana

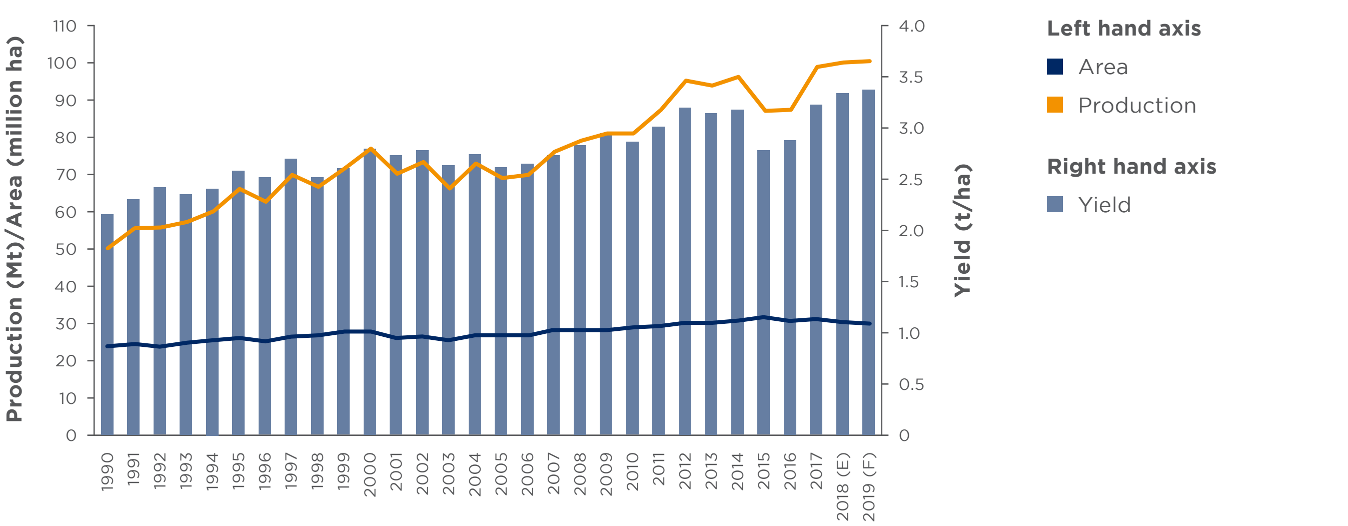
106. India is the second-largest consumer nation of mineral nitrogen fertilizer in the world after China.[169] Since the 1960s much of India's agriculture has been characterized by the high use of mineral nitrogen fertilizer. This has led to low NUE, which in the last decade has stabilized around 40%.[170] Nitrogen input into cropping systems increased in India by 149% from 1990–2019, while harvestable output (total cereals) only increased by 67%.[171]

107. India is also one of the larger agricultural producing nations in which urea is the main source of mineral nitrogen fertilizer – around 81%.[172] This means it also has a significantly higher proportion of carbon dioxide emissions from fertilizer use in comparison with other countries in this study.

108. Both the fertilizer industry and the agricultural sector more generally in India have higher levels of government intervention compared with other countries. Fertilizer, especially urea, is highly subsidized through the provision of neem-coated urea at a fixed cost across the country[173] well below the cost of production. This fertilizer saw a price increase of just 11% between 2000–2020,[174] whereas international urea prices had nearly tripled in that time, before price volatility started in 2020.[175] Agricultural output is also subject to minimum-price controls.[176]

109. The most common crop rotation found in India and other south Asian countries is rice-wheat. This is particularly dominant in states such as Punjab, Haryana, Bihar, Uttar Pradesh and Madhya Pradesh, contributing to 75% of the national food grain production.[177] The states of Punjab and Haryana have the highest yields in the country of both rice and wheat, delivering 15% and 30% of total national production for each respective crop.[178]

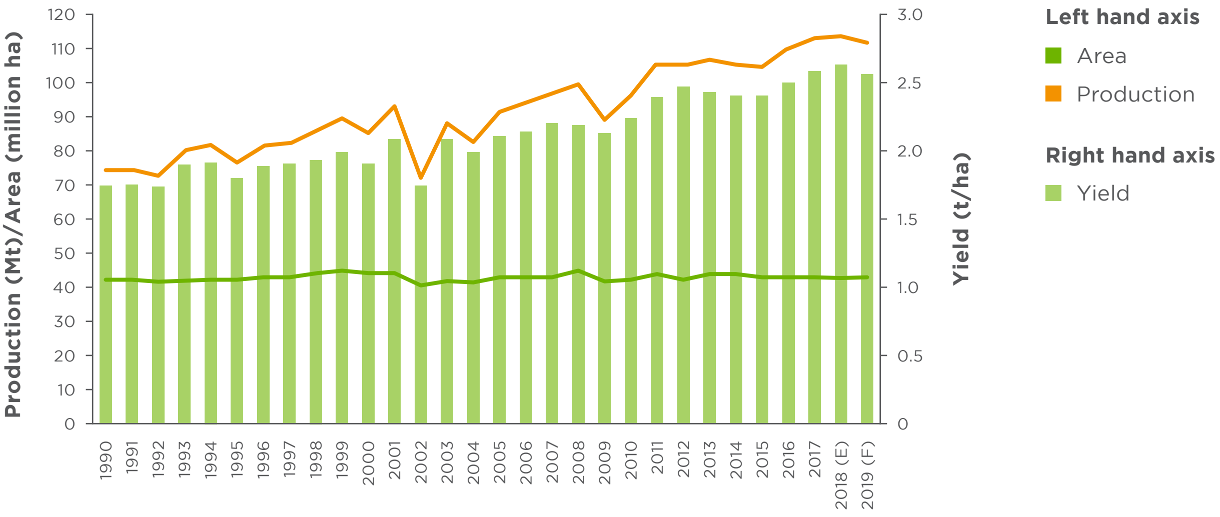
Figure 10. Wheat cultivation in India



(E) estimate; (F) forecast.

Source: *Ministry of Agriculture and Farmers Welfare (MoAFW), Government of India (GOI); and FAS/New Delhi forecast for 2019 (MY 2019/20) via USDA*[179]

Figure 11. Rice cultivation in India



(E) estimate; (F) forecast.

Source: *Ministry of Agriculture and Farmers Welfare (MoAFW), Government of India (GOI); and FAS/New Delhi forecast for 2019 (MY 2019/20) via USDA*[180]

Improving NUE through mobile technology extension services

110. Extension services are underdeveloped in India and dispersed rural populations are often out of the reach of in-person agronomic advice, with only 6% of the agricultural population reporting contact with these services.[181] Mobile phone technology can be used to provide information and advice on balanced crop nutrient management and other agronomic issues to previously unconnected and hard-to-reach farmers. If delivered at scale, extension services through mobile phones could deliver far greater reach more cost effectively than in-person advice.

111. Estimates for optimum mineral nitrogen fertilizer application rates, balancing nitrous oxide emissions and the relationship between yield growth and marginal rate of return, are within a wide corridor between 120 and 200 kg N/ha for rice, and 50 and 185 kg N/ha for wheat.[182] Further studies have identified an economic optimum nitrogen application rate at 130 kg N/ha for rice in the region.[183] However, average application rates of mineral nitrogen fertilizer in Punjab and Haryana are 175 kg N/ha and 163 kg N/ha respectively, implying that reductions can be made to address emissions from the use-phase while not impacting yields.

112. A scenario in which mobile extension services reached farmers covering 2.3 million ha (50% of cultivated area of rice) and encouraged them to reduce mineral nitrogen fertilizer input by 20% on average could achieve emissions reductions of 1.5 Mt CO_2e of nitrous oxide and 0.5 Mt of carbon dioxide.

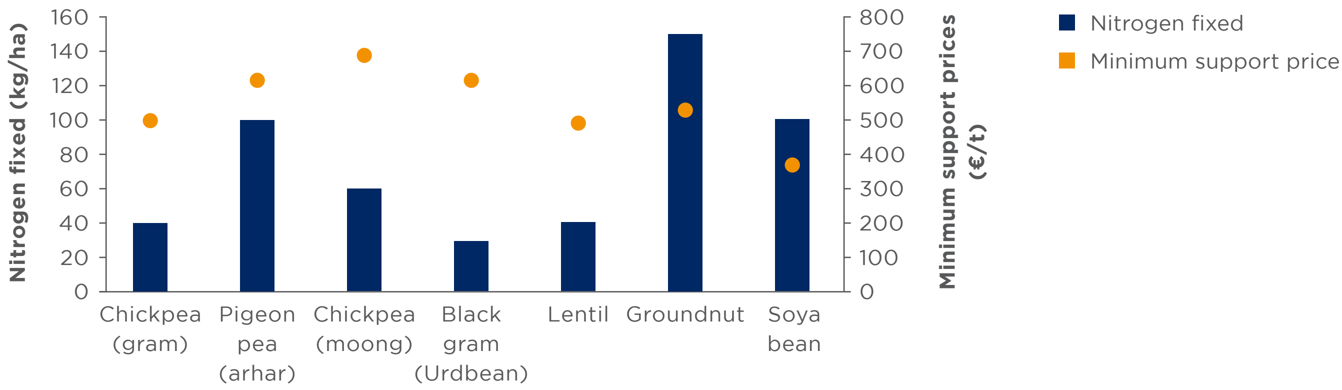
113. Support services could lead to ongoing yield growth, even as mineral nitrogen fertilizer inputs are reduced. If yields continue to grow by 10% annually in the short term, closing the yield gap to maximum potential yield, this could deliver farmers an incremental €179/ha/yr in revenue. As fertilizer is subsidized, input cost savings for farmers from using these services would be minimal, but assuming a modest cost to access the service, farmers could still see a net benefit of €72/ha/yr. This equates to an abatement saving of €172/t CO_2e.

Improving crop rotations

114. While historically a net exporter of soya beans, growing domestic demand has made India a net importer of the crop in recent years. Soya beans are the most popular animal feed protein source, used across India's entire meat production industry.[184] Demand is growing for animal feed but also as a potential replacement for other edible oils, of which India is also the world's biggest importer.[185]

115. Soya beans have been modelled in this example to support comparison across global systems. Other legumes more suitable for human consumption and local diets that achieve different levels of biological nitrogen fixation could be used as alternatives in a diversified crop rotation. These legumes may also command a higher sale price and therefore reduce the potential cost of crop diversification.

Figure 12. Biological nitrogen fixing potential and minimum support pricing for legumes in India



Source: *Government of India[186], Das & Ghosh (2012)[187]*

116. Current soya bean cultivation in Punjab and Haryana is negligible, but average yield for soya beans in the rest of India is 1.2 t/ha,[188] well below average yields globally and from key exporting countries. Nevertheless, field studies have shown that yields of >2.5 t/ha in the region are possible.[189]

117. Assuming soya beans could take 15% of the land in the rice–wheat rotation region and replace rice within the rotation (with increasing rice productivity leading to constant rice output), emissions savings thanks to the biological nitrogen fixing effect of the crop and reduced mineral nitrogen fertilizer inputs could be 1.2–2.4 Mt CO_2e. However, current domestic pricing on soya beans means that farmers' net financial position would be -€626/ha/yr, or -€629/ha/yr if other measures have already been applied. This is a marginal abatement cost of €525–€1,051/t CO_2e, or €569–€1,138/t CO_2e if other measures have already been applied.

Measurement, reporting and verification (MRV) and the frameworks for companies to claim Scope 3 emissions reductions

118. The top-down scenario and regional analyses presented in this report show significant potential for reducing greenhouse gas emissions from mineral nitrogen fertilizer use. However, multiple science-based frameworks for determining Scope 3 emissions, and what can be considered as a reduction against these, can make it challenging for for fertilizer companies to set targets.

119. The first challenge is demonstrating the emissions savings resulting from interventions. Emissions from agricultural land and practices are influenced by multiple factors, including but not limited to: soil moisture; temperature; oxygen concentration; and the amount of available organic carbon and nitrogen, and the soil carbon to nitrogen ratio.[190] There is inherent variability in the outcomes of these processes in a biological system, meaning that the same activity on one side of a farmer's field can have different emissions outcomes as the same activity on the other side of a field. Accounting approaches for agricultural emissions mostly take modelled approaches, which represent averages of expected outcomes for practices but never the actual emissions for any given field, although this is not dissimilar to many other sectors and sources of emissions.

120. As set out in Chapter 1, the IPCC uses a linear formula to estimate nitrous oxide emissions based on the amount of nitrogen input from mineral nitrogen fertilizer applied. At Tiers 1 and 2, it does not take into account NUE and surplus directly, but a practice change that reduced the nitrogen input and increased NUE as a result would be considered as a reduction in emissions.[191] The IPCC guidance also allows for a reduction in emissions factors where activity data can be found to demonstrate the impact of interventions.[192]

121. Higher granularity of activity data on farm practice changes can improve the accuracy of models. There remains a lack of high density, spatiotemporally relevant measurement of nitrous oxide emissions from managed soils using mineral fertilizer or a clear path to address this in the medium term. However, modelling can be improved significantly by increased volume of more accurate activity data from farms in order to assess implementation of practice changes. This could be supported with more innovative approaches to data collection such as remote sensing.

122. Lack of accurate activity data to increase robustness of modelled approaches may foster a conservative approach taken by companies to avoid overclaiming, and therefore inhibit corporate action when the potential outcome and impact seems limited. Fertilizer companies who can do so should support activity data collection and measurement. This would lower this barrier for other companies to invest in potential mitigation action.

123. The second challenge is that, while the interventions laid out in this report would all act towards the entire sector reducing its emissions from the use of fertilizer, the current framework of greenhouse gas emissions reporting protocols and accounting methods may make it difficult for an individual company enacting a plan to deliver these to be able to claim a reduction in their Scope 3 emissions inventory.

124. There are two key limiting factors to attributing a Scope 3 reduction to a company:

- Mitigation activity must be considered within the definition, boundary and categorization of Scope 3 activity (e.g. the GHG Protocol Scope 3 category on emissions from the use of sold products); any activity that falls outside of this cannot be considered as a Scope 3 reduction; and
- Mitigation activity must be within a company's own value chain and operations; company efforts must be driving the change to reduce emissions from their own products and services.

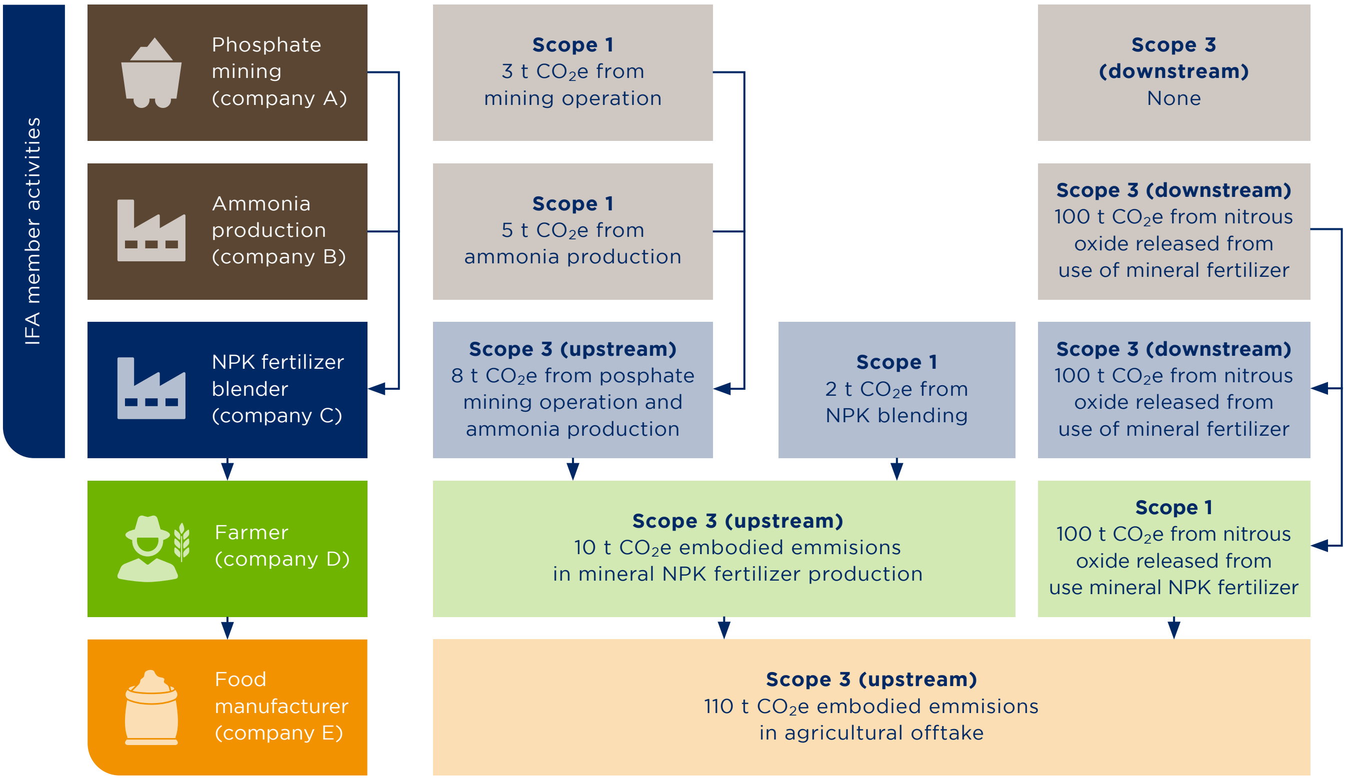
125. Even if such a reduction has been determined empirically, if there is uncertainty around these points, companies are unlikely to be able to claim a Scope 3 reduction.

Products in scope

126. Nitrous oxide emissions released from the use-phase of mineral nitrogen fertilizer are linked to the total amount applied and the nitrogen content of a given fertilizer product. They are also, to an extent, inherent to the fertilizing quality of the product.[193] A similar principle applies to the use of urea, where the release of carbon dioxide on application to soil is an unavoidable process linked to the chemical composition of these products.

127. Companies who manufacture these products, whether as an intermediate product or a final product for farmers, therefore have these nitrous oxide and carbon dioxide emissions within their Scope 3 inventories (Figure 13).[194 j] There may be some difference when a fertilizer company sells chemical rather than mechanical blends. For mechanical blends, only suppliers of intermediate ingredients related to nitrogen are likely to be responsible for nitrous oxide emissions, as the other ingredients do not impact or facilitate the release of emissions. In chemical blends, where the chemical compound is a more intrinsic link and non-nitrogen ingredients may exacerbate or reduce nitrous oxide emissions, all ingredient suppliers may bear some responsibility, proportionate to impact, for emissions at point of use by farmers.

Figure 13. Example of emission scope reporting and overlap between different entities in the mineral fertilizer value chain (illustrative numbers only)



Source: *GHG Protocol Corporate Value Chain (Scope 3) Accounting and Reporting Standard*[195]

Interventions and measures to help farmers improve NUE

128. For a fertilizer company working with farmers (customers) in its downstream value chain to improve NUE through better implementation of the 4Rs of nutrient stewardship, it may count any emissions reductions towards a Scope 3 reduction if:

- the company's products are associated with greenhouse gas emissions when used in the value chain; and
- the farmers adopting the improved practices use that company's products.

129. If there is uncertainty about whether farmers have used the company's product, it cannot be considered a Scope 3 reduction, as the activity may be outside the company's value chain. With farmers forming a huge and fragmented customer base for fertilizer companies, this adds an extra challenge.

130. The act of a company commissioning an activity to reduce nitrous oxide and carbon dioxide greenhouse gas reductions from mineral nitrogen fertilizer use more generally (i.e. outside its own value chain) would be considered as beyond value chain mitigation, even if the intervention is in an adjacent activity to their own Scope 3 emissions. Beyond value chain mitigation must be in addition to (rather than instead of) value chain emissions reductions. In cases where it is instead of value chain emissions reductions, it is often referred to as offsetting.[196]

Use of enhanced efficiency fertilizers and inhibitors

131. Enhanced efficiency fertilizers and inhibitors can address emissions from the use-phase by improving NUE, reducing indirect emissions from ammonia volatilization and inhibiting the nitrification process to protect against both denitrification and leaching.[197]

132. If a fertilizer company's portfolio already contains enhanced efficiency products and nitrogen fertilizer combined with inhibitors, an appropriate science-based reduction factor should be applied to the baseline calculation for Scope 3 emissions, lowering the company's baseline emissions.

133. If a company takes action to shift its portfolio and product mix from conventional nitrogen fertilizer to slow- and controlled-release or stabilized fertilizers, or for usage in conditions where application is more controlled, such as in precision agriculture, and therefore has a change in product mix and sales volume, it should be able to claim a Scope 3 reduction relative to its baseline using an appropriate science-based reduction factor.

134. However, a company comparing its enhanced efficiency product with another company's conventional product cannot claim an emissions reduction through taking market share. This is instead known as an avoided emission.[198] A similar circumstance is when a company compares the emissions reduction with a hypothetical scenario where the product does not exist and claims an emissions reduction on this basis. The Science Based Targets initiative (SBTi) introduced in Chapter 1 is unambiguous in that avoided emissions claims cannot be used in Scope 3 inventories.[199]

Wider food-system changes, such as diversifying crop rotations

135. Wider changes to the agri-food system that indirectly affect the use of fertilizer and reduce emissions from the use-phase, such as diversification of crop rotations, are unlikely to be attributable to a fertilizer company as a reduction in its own Scope 3 emissions, even if it works with farmers to support this transition. However, if a system-level change happens that reduces the use of nitrogen fertilizer and therefore company sales volume, this contraction would be recorded as an emissions reduction.

Avoided deforestation

136. The use of mineral fertilizer allows the production of more food on a fixed amount of land, therefore reducing the aggregate need for deforestation and land conversion. Under current protocols, emissions associated with claims of avoided deforestation claims cannot count towards a Scope 3 reduction as they do not fall within the value chain of a company. They would fall into the territory of avoided emissions, which cannot be included in reductions targets because they relate to a hypothetical situation in which a product does not exist. This does not change the imperative that all stakeholders in the agri-food value chain must not resort to clearing more land to produce food while reducing emissions from mineral nitrogen fertilizer.

What does this mean for the fertilizer sector?

137. This is a continually evolving space. In addition to the development of a Sectoral Decarbonization Approach, there is a variety of forthcoming publications, methodologies and projects that can help fertilizer companies to reduce their Scope 3 emissions in line with science-based targets. Among them are: the GHG Protocol Land Sector and Removals Guidance; SBTi Forest, Land and Agriculture project (FLAG); SBTi Beyond Value Chain Mitigation; SBTi Net-Zero Value Chains; and SBTi Measurement, Reporting & Verification. Under the emerging SBTi FLAG guidance, companies who are required to set a FLAG-specific target (specific land intensive sectors related to agricultural production, and companies with 20% of revenue or emissions coming from FLAG activities and therefore most fertilizer companies) will be required to publicly commit to zero deforestation covering all scopes of emissions.[200]

138. Farmers as a stakeholder group may have less capability and capacity to engage with the development of these processes and methodologies. While this is a generalization at a global level – and there will be farmers who act counter to this – the majority of food production is estimated to come from millions of smallholder farmers who operate under multiple pressures. Fertilizer companies should continue to participate to ensure they reflect the realities, complexities, challenges and opportunities for farmers in the development of MRV for emissions from on-farm fertilizer use and work with other food system participants to reduce on-farm emissions, thereby reducing industry Scope 3 emissions.

NOTES

a. Precision agriculture has no universally aligned definition but can be considered as guidance technologies of machinery, recording, and measuring technologies of soil qualities, and reacting technologies that respond with variable rates of fertilization and other inputs. Refer to Balafoutis, A., Bert, B., Fountas, S., Vangeyte, J., Van Der Wal, T., Soto Embodas, I., Gomez Barbero, M., Barnes, A. and Eory, V. (2017). Precision Agriculture Technologies positively contributing to GHG emissions mitigation, farm productivity and economics, SUSTAINABILITY, ISSN 2071-1050, 9(8), p. 1339, JRC106659.

b. Assumes 0.4%–0.6% growth in nitrogen uptake by crops per year, and the gap in mineral nitrogen fertilizer application per hectare between Africa and the global average is closed by between one and two thirds.

c. Assumes biological nitrogen fixation reduces mineral nitrogen fertilizer requirement of the following crop by 20%–40%.

d. This column illustrates some of the uncertainty around estimating emissions. It shows what happens to emissions estimates if the IPCC direct emissions factor, as well as fractions of fertilizer that are volatilized or leached, are adjusted in proportion to improvement in NUE relative to the 2020 baseline. This follows Chang (2021), though that paper has a more localized approach to leaching impacts. It is, however, also possible that emissions factors could increase with climate change causing warming soils and wetter conditions.

Griffis et al. (2017) Nitrous oxide emissions are enhanced in a warmer and wetter world. *Biological Sciences*, 114 (45), 12081-12085.

e. Einarsson et al. (2021) provides estimates of total nitrogen flows for France. The average 2015–2019 is taken and scaled for the area of crops under consideration. The reduction in nitrogen inputs to raise NUE to 76% is then calculated and allocated entirely to a reducing in mineral nitrogen fertilizer, based on data on fertilization of these crops from AGRESTE (2021).

f. €26/ha saving divided by the emissions saving of 0.15 t CO_2e.

g. 60%–80% of the area to which urea is applied, given urea makes up around 21% of nitrogen fertilizer in France by nitrogen content. Source: IFASTAT.

h. Based on average maize yield from 2017 to 2021 and producer prices from 2016 to 2020.

i. Based on a nitrification inhibitor price of €25 to €40/ha, applied to an additional 52% of the maize area, which is in turn around 53% of the Iowa crop area. Carlson (2021), Trenkel (2010), USDA (2022).

j. In certain cases, the eventual end use of sold intermediate products may be unknown. For example, a company may produce an intermediate product with many potential downstream applications, each of which has a different GHG emissions profile, and be unable to reasonably estimate the downstream emissions associated with the various end uses of the intermediate product. In such a case, companies may disclose and justify the exclusion of downstream emissions from categories 9, 10, 11 and 12 in the report (but should not selectively exclude a subset of those categories).

CHAPTER 3

How can the fertilizer industry maximize soil carbon sequestration to address Scope 3 emissions?

As a key actor within the forest, land and agriculture (FLAG) sector, the fertilizer industry will be able to count carbon dioxide removals, such as soil carbon sequestration (SCS), towards a science-based decarbonization target. Optimum mineral nitrogen fertilizer is necessary for both reaching the right carbon to nitrogen (C:N) ratio in soil organic matter, as well as for producing above- and below-ground biomass, both of which being critical to capture carbon in soils. Nevertheless, there can be a trade-off between managing mineral fertilizer to reduce emissions and to sequester carbon, as applying mineral nitrogen fertilizer to stimulate sequestration will also lead to nitrous oxide emissions.

Phosphorus also plays a key role in increasing biomass production in phosphorus-fixing soils, which are widespread in the tropics. Increasing soil carbon stocks in this way also brings wider soil health and other co-benefits.

Developing and growing carbon markets, both voluntary and compliance-based, is one way to help support finance for SCS. Fertilizer companies can also take action within their own value chain to enhance SCS (also known as "insetting"). Crucially, fertilizer companies need to act not only to support farmers to achieve the potential contribution of SCS to climate change mitigation, but also to ensure the sector can be credited for its efforts in this space.

Soil carbon sequestration is the carbon dioxide removal that optimum mineral fertilization can support most readily and economically

1. Meeting the Paris Agreement goals will require deep decarbonization across all industries, with sustained and rapid greenhouse gas emissions reductions. Chapter 2 set out ways to reduce the fertilizer sector's Scope 3 emissions from the use of mineral nitrogen fertilizer in the field by farmers.

2. Even with the most ambitious emissions reduction scenarios, there will remain an overshoot that exceeds the "carbon budget" that would keep the planet on a 1.5°C pathway for 2050. There will also be ongoing emissions from certain industries after 2050 that still cannot be abated, including the fertilizer industry, as outlined in Chapter 2.

3. Therefore, to reach long-term temperature goals, in addition to emissions reductions, there is a need for carbon dioxide removals (CDR) to offset the overshoot in carbon budgets before 2050 and neutralize hard-to-abate residual emissions thereafter. These removals are in addition to rapid and sustained emissions reductions across all sectors and not a replacement for this.

4. Technically feasible CDR solutions (see Figure 1) can be categorized into:

- natural climate solutions (NCS), such as restoring forests and other ecosystems that can sequester carbon;
- engineered approaches such as Direct Air Carbon Capture & Storage (DACCS), that remove carbon dioxide from the atmosphere for storage in geographical reservoirs or in other long-lasting forms; and
- hybrid approaches between these two types that use biomass and capture carbon in a longer term, more stable form compared with natural solutions, such as Bioenergy with Carbon Capture and Storage (BECCS).

5. Other removals may exist in the future, such as ocean mineralization and fertilization, but remain at present speculative and have a low chance of being delivered at scale by 2050.[201] It is estimated that cost-effective (< US$100 per tonne) natural climate solutions will provide 20% of the total necessary CO_2 mitigation between now and 2050[202] and provide mitigation potential at a global level of 8–13.8 Gt CO_2 a year.[203] At the same time, investment must continue to flow into protecting existing nature and carbon stocks.

Figure 1. Carbon dioxide removals (CDR) summary table

Type	Principle	Method	Solution	Activity
Natural Climate Solutions (NCS)	Restore	Using forestry (including outputs for storage in usage) and other ecosystems to capture carbon	Restore forests	Reforestation
				Afforestation
			Restore other ecosystems	Restore peatland
				Blue carbon (mangroves, marshes, coastal wetlands)
	Manage		Agroforestry	Integration of trees into agricultural land (alley cropping, silvopasture etc.)
			Improved forest management	Improved forest management (e.g. reduced-impact logging, extended harvest rotation, thinning)
		Using soil to sequester carbon	Enhance soil carbon sequestration (SCS)	Enhance soil carbon sequestration in degraded cropland
				Enhance soil carbon sequestration in degraded grazing lands
Biomass with Carbon Removal Solutions (BiCRS)		Using agricultural outputs to capture carbon in more sustainable manner (storage-with usage)	Biochar from crop residues	Thermal decomposition of biomass in the absence of oxygen to a more decomposition resistant form
	Purpose built		Bioenergy with Carbon Capture and Storage (BECCS)	Burning of biomass to capture CO_2 and place in geographical storage
Engineered		Using tech to sequester carbon from atmosphere	Direct Air Carbon Capture and Storage (DACCS)	Direct air capture and geographical storage of CO_2

Primary focus for the fertilizer industry

Secondary focus for the fertilizer industry

Source: *Adapted from "Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonization to Keep 1.5°C Alive" from the Energy Transition Commission – March 2022.*[a]

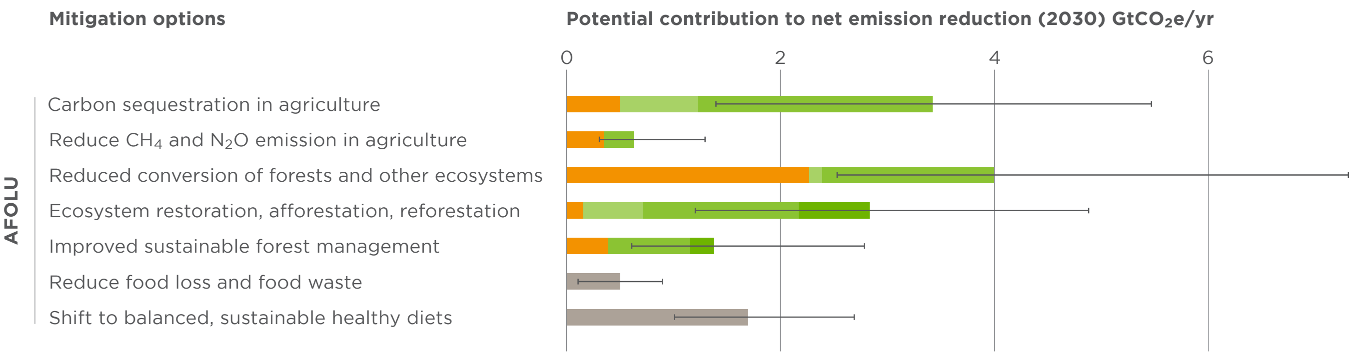
6. The fertilizer industry has a role to play in or the potential to interact with many removals, particularly natural climate solutions and natural removals since nearly all involve the growth of biomass.

7. The most relevant removal opportunity for the fertilizer industry is enhancing soil carbon sequestration (SCS). SCS is one of the main flows of carbon in the environment, with carbon dioxide in the atmosphere being transferred to land-based forms in soil.[204] All mineral soils sequester carbon dioxide from air, either as SOC, primarily from biomass where plants have absorbed carbon dioxide through photosynthesis, or through the conversion of atmospheric carbon dioxide into inorganic forms such as carbonates.[b]

8. Enhancing SCS requires changes in agriculture techniques and practices[c] to increase levels of SOC in grasslands and croplands through a combination of increased biomass production and recycling as well as reduced soil mechanical disturbance (e.g. tillage). SCS is one of the few widely available CDR methods, along with forestry-related solutions.[205] It should be noted that the net sequestration of organic carbon in soils requires significant amounts of nutrients such as nitrogen and phosphorus to form stable organic compounds, including nutrients from fertilizers.[206]

9. The Intergovernmental Panel on Climate Change (IPCC) has estimated the potential for SCS in croplands at 1.9 Gt CO_2/yr with a wide confidence interval of 0.4–6.8 Gt CO_2/yr, and in grasslands of 1.0 Gt CO_2/yr with a narrower confidence interval 0.2–2.6 Gt CO_2/yr. Other estimates put SCS potential at a range of 0.2–5 Gt CO_2/yr, with most estimates towards the lower end of the range, and some as low as 0.4–0.8 Gt CO_2/yr.[207] Taking account of cost effectiveness reduces the potential further. The IPCC estimates that 0.6 (0.4–0.9) to 0.9 (0.3–1.6) Gt CO_2/yr of SCS is available at less than US$100/t CO_2 respectively for cropland and grassland, drawing on estimates from Roe et al (2021).[208] Despite a wide range of uncertainty, SCS is second only to avoiding further land conversion in terms of potential contributions from the agriculture, forestry and other land use (AFOLU) sector in emissions mitigation potential (see Figure 2).

Figure 2. Potential contribution between different mitigation options and net lifetime costs



Net lifetime cost of options

- Costs are lower than the reference
- 0-20 (USD/tCO_2e)
- 20-50 (USD/tCO_2e)
- 50-100 (USD/tCO_2e)
- 100-200 (USD/tCO_2e)
- Cost not allocated due to high variability or lack of data
- Uncertainty range applies to the total potential contribution to emission reduction. The individual cost ranges are also associated with uncertainty

Source: *IPCC*[209]

10. Practices to increase SCS on cropland include but are not limited to: use of cover crops,[210] deep tillage,[211] cultivation of perennials, fallow reduction,[212] diversification of plant cultivation,[213] irrigation management[214] and the optimization of fertilizer use.[215] Optimal fertilizer use leads to increased biomass production, both above and below ground, and the retention of these residues increases SOC.[216]

11. On managed grasslands, practices include planting more diverse grass varieties with deeper roots, controlled fire management, and changes to animal stock density and grazing methods.

12. Fertilizer optimization on cropland and grassland is the practice that is most directly linked to the fertilizer industry. Other practices have a lesser role for mineral fertilizer use though it may support the implementation of some.

13. Different nutrients have different impacts on SCS. Mineral nitrogen fertilizer is characterized by two contrasting trends. On the one hand it fuels biomass production, which increases SOC stocks, but on the other hand in excess it may stimulate biodegradation of soil organic matter and reduce SOC stocks.[217] Phosphorous fertilizer can positively affect the carbon storage capacity of soil and carbon dioxide flux via several mechanisms, such as metabolic processes and respiration of soil and crop root growth.[218][d] Phosphorus fertilization is particularly important to stimulate biomass production in the tropics, where phosphorus-fixing soils are widespread.

14. The carbon-to-nitrogen (C:N) ratio in soil and in organic matter applied to soil also play a role in regulating the microbial activity that affects soil carbon storage. All other things being equal, sequestering more carbon in the soil requires adding more of both nitrogen and carbon. Therefore, mineral nitrogen fertilization that optimizes the C:N ratio by soil type, and crop residues being returned to soil, can support enhanced SCS.

15. In the deep, acidic and highly weathered soils commonly found in the tropics, carbon sequestration in deeper layers represents a further opportunity, though this can require improvements to the soil structure. Adding lime and/or phosphogypsum to the soil increases calcium and sulphur content and so increases soil pH, root system development, carbon input to the soil and NUE.[219] One study found that this could lead to the sequestration of 5.4 t/ha of carbon in the first metre of soil after four years of application, with most of this carbon being sequestered in deeper layers over the long term.[220] Overall, there is evidence to suggest that, across multiple crop systems, SCS is enhanced by balanced fertilization and by optimizing fertilization according to regional agro-climatic conditions.[221]

Beyond the carbon removal effect, SCS brings wider benefits for farmers and the ecosystem

16. Most changes required of farmers to enhance SCS are generally considered part of general good agricultural practice and have co-benefits for farmers and their land, particularly improved soil health, better nutrient cycling, higher yields, increased resilience to drought and disease, and potential reductions in input costs. These include cover crops, cultivating crops with deeper root systems and irrigation management. However, some of the evidence on co-benefits is mixed, and some measures may have a negative effect on yields in some circumstances.[222]

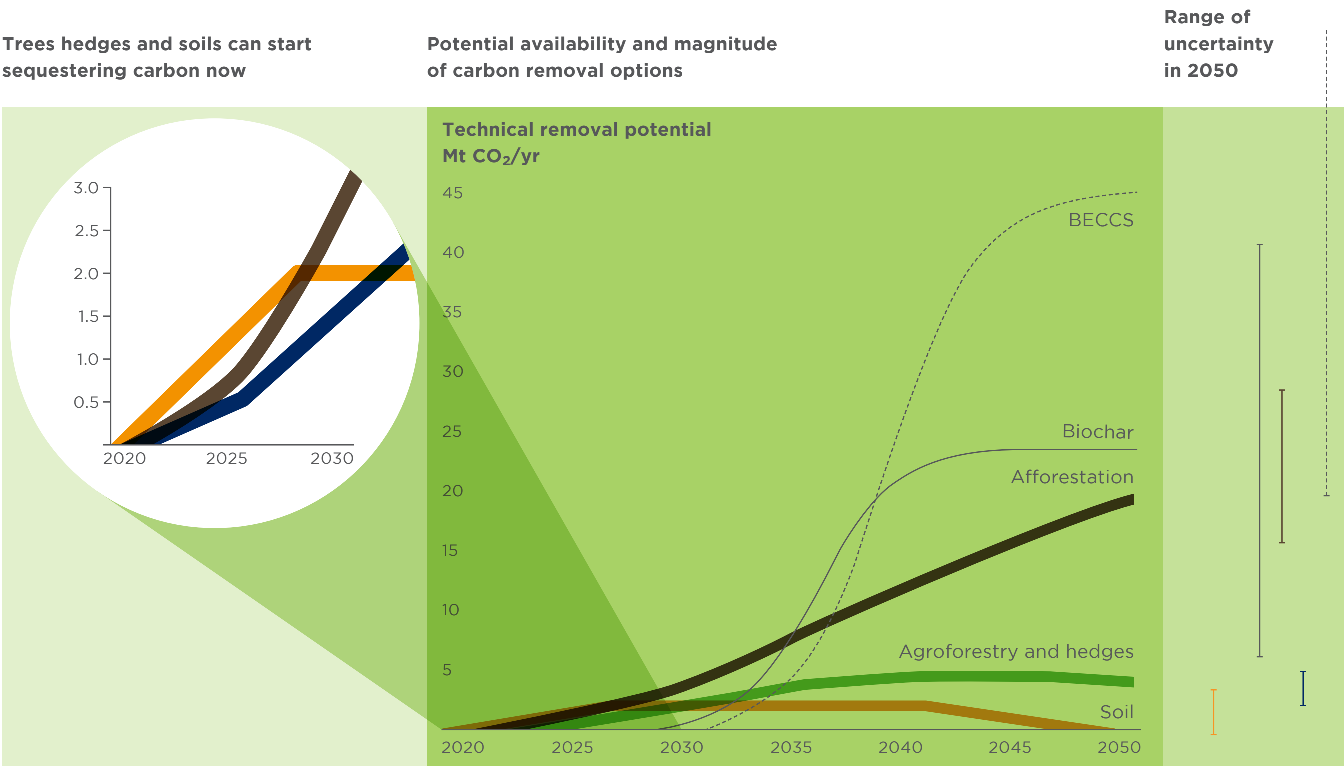
There are natural limits to SCS potential, and its impact is currently difficult to measure accurately or cost-effectively

17. There are natural limits on the amount of carbon that soils can hold, as well as the scope for biomass generation above and below ground. There may also be photosynthetic limits to the amount of carbon that soils can retain.[223]

18. There are also limits to the benefits to yields of improved soil health. While improved soil health and SOC content can have a positive impact on yield, the relationship is non-linear. Yield increases will plateau above a certain level of SOC before other nutrients and fertilizer inputs are required to drive further increases.[224]

19. The sequestration profile of soil is a further challenge. On adoption of best practices, long-term crop trials suggest there is an initial increase in carbon stored at the sub-surface level, eventually reaching a new, higher steady state. The higher speed of initial sequestration in soil compared with other CDR must be balanced against the limited long-term potential volume of carbon it can sequester.

Figure 3. Comparative carbon sequestration profile of different carbon removals modelled for the United Kingdom



Source: *Green Alliance – The Opportunities of Agri-Carbon*[225]

20. Carbon sequestered in soils is commonly assumed to be susceptible to early-release events. This means that the stored carbon can be easily released if practices change. Climate change-induced extreme weather that impacts soil moisture – such as droughts and flooding – could also limit and then reverse carbon sequestration.[226] There is significant uncertainty, however, with some studies disputing these concerns.[227]

21. Measuring SOC content is challenging, which creates a barrier for large-scale adoption of schemes to improve SCS.[228] Soils are biological systems with high levels of inherent spatiotemporal variability, particularly in SOC stocks. This does not match well with sampling procedures that are costly and labour intensive. Modelling is a more cost-effective approach than sampling and laboratory analysis, but any model requires robust input activity data to be accurate.

22. Improved, credible and reliable measurement, reporting and verification (MRV) would help to address some of these, but this is a less significant problem compared with nitrous oxide measurement. In the meantime, current methods of measurement of changes to SOC content and adoption of broad practices known to improve SOC relevant to local agroclimatic regions still offer a scalable solution to estimate impact.

23. Finally, there is a trade-off between nitrous oxide emissions and SCS. The main mechanism for increasing SOC and therefore sequestration is the increase of both above- and below-ground biomass, which requires using fertilizers, especially nitrogen. This will inevitably be associated with some nitrous oxide emissions, offsetting at least some of the gains achieved through SCS.[229]

Carbon markets can accelerate the transition and channel finance into carbon farming but are underdeveloped at present

24. While some farmers recognize the economic value in the benefits of focusing on improving soil health through carbon sequestration, others will require more external stimulus and investment to adopt new practices.

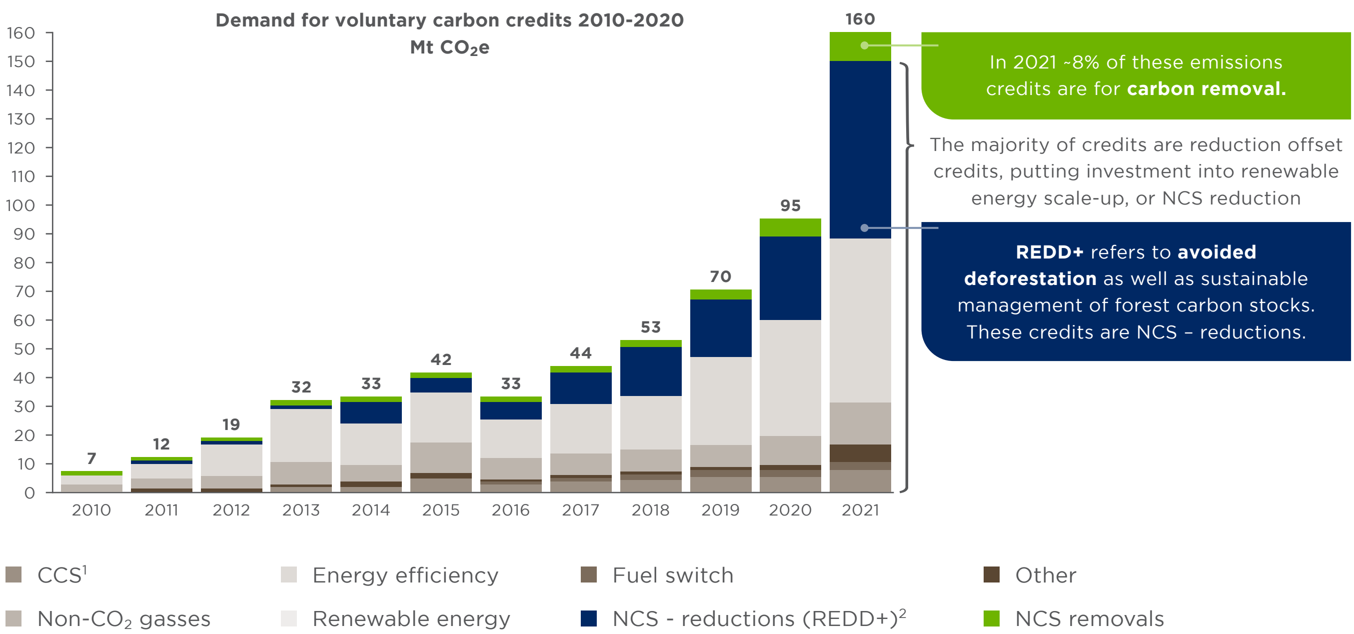
25. Carbon markets provide a framework for such a transaction, connecting farmers who adopt and maintain SCS practices with those looking to offset their emissions or neutralize their remaining unabated emissions.

26. There are two types of carbon markets: compliance-based and voluntary. Compliance markets are created and regulated by governments to help achieve carbon reduction and removal targets. To date, the Nitrous Oxide Emission Reduction Protocol (NERP) from Alberta in Canada and the Australian Government's Emissions Reduction Fund are the only compliance schemes that have issued credits for soil management projects.[230] Uptake has been low, in part owing to scepticism from farmers, even those who already practise soil conservation.[231] They may also be concerned about potential future requirements to offset their own farm's operational emissions.[232]

27. There is growing interest in SCS through voluntary markets, with demand coming from companies looking for mitigation opportunities outside their value chain. There is an increasing number of project developers, brokers and investors connected to purchasers of credits who wish to offset emissions within their own operations and value chain.

28. The carbon market ecosystem is still developing, especially in the space of removals, though the land-use-related natural climate solutions only receive a small proportion (<2.3%) of both public and private climate finance.[233] The majority of carbon credits purchased in voluntary carbon markets so far have been emissions reductions rather than removals (see Figure 4). Projects generating such credits include energy efficiency schemes and avoided deforestation projects (through the United Nation's REDD+ mechanism). Carbon removals from natural climate solutions only amounted to 8% of total credits in 2021, though this is more than double what was purchased just two years ago.[234]

Figure 4. Demand for voluntary carbon credits 2010–2020



[1]Assumed that the vast majority of CCS credits are for point-source CCS, and therefore a reduction credit.
[2]REDD+ refers to Reduced Emissions from avoided Deforestation and forest Degradation, as well as the sustainable management and enchancement of forest carbon stocks.

Source: *Energy Transition Commission (2022) "Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive", from Trove Intelligence Research (2021) Future Deman, Supply and Prices for Voluntary Carbon Credits - Keeping the Balance. 2021 data sourced from Climate Focus (2022), Voluntary Carbon Market Dashboard.*

29. MRV of soil carbon sequestration protocols and methodologies is still an area under development. Gold Standard has developed a Soil Organic Carbon Framework for quantifying and approving adoption of different practices, though as of yet the only approved activity modules for SOC sequestration are improved tillage practices and application of pulp and paper mill sludge.[235] Meanwhile, Verra's previously approved methodology for Soil Carbon Quantification (VM0021) has had a status of On Hold since March 2022, to allow substantive revisions to baseline SOC stocks in land and a better understanding of the overlap with other agricultural and land methodologies.[236]

30. Investment in carbon credits provides corporate entities with a way to neutralize residual emissions that cannot be abated. SBTi does not recognize carbon credits or other removals as a substitute for emissions reductions.[237] Corporate claims of climate neutrality or climate positivity through the purchase of credits will therefore not be recognized by SBTi, other than those defined as hard-to-abate as detailed in this report.

31. The draft guidance for the food, land and agriculture sectors (SBTi FLAG) proposes a different treatment for emissions from these sectors, given that abatement and removals in the agriculture, forestry and other land use sectors often go together. SBTi therefore propose that removals can count towards a science-based target for FLAG activities only for companies that earn more than 20% of their revenue in the agriculture sector and generate more than 20% of their emissions there.[238]

32. Fertilizer companies looking to increase removals through enhanced SCS have two potential routes leading to two different benefits:

- Financial – Help farmers generate and sell carbon credits but receive no emissions accounting benefit, becoming a value-sharing partner to the farmer by helping them to adopt the required practices and comply with the third-party standards. These credits cannot count towards the fertilizer company's science-based target as the offset would belong to another entity or individual and carbon credits cannot be claimed twice; and
- Emissions accounting – Help farmers adopt the required practices, being able to claim the removal in their emissions accounting but with no carbon credit being generated. In this circumstance, the fertilizer company may be able to count the removal towards a science-based FLAG target. If this activity fell outside the boundary of its own value chain, it would be considered beyond value chain mitigation.

The fertilizer sector should support farmers to enhance SCS through product sales and advice, and use its agronomic expertise to support further development of SCS protocols

33. Some of the practices to reduce greenhouse gas emissions from mineral nitrogen fertilizer use, outlined in Chapter 2, also increase SCS. The sector should focus on ensuring farmers have access to the right portfolio of mineral nitrogen fertilizer products and using balanced nutrient management. That includes use of phosphorous and other nutrients to maximize biomass and SOC for sequestration, following the 4Rs principles. The sector should also consider how it can support farmers with the successful adoption of other practices that have a benefit to SCS, using balanced mineral fertilization.

34. The sector should continue to engage with the development of carbon credit methodologies for enhancing soil carbon and the adoption of more cost-effective MRV technologies. This will help to ensure that the standards reflect the latest science in balanced nutrient management for SCS and address challenges such as permanence and saturation. The sector can play a role in stimulating both the supply and demand side of agri-carbon markets to ensure that required investments in the field are reached. Through these efforts, soil carbon projects can grow in line with expected expansion of other voluntary carbon markets.

35. Finally, SBTi FLAG targets will allow the inclusion of removals towards a target in the AFOLU sector. Fertilizer companies may therefore be able to supplement emissions reduction efforts (such as NUE) with balanced nutrient management practices that sequester carbon – and be credited for both to reach a science-based target. As described above, any action will need to balance SCS with nitrous oxide emissions from mineral nitrogen fertilizer use.

NOTES

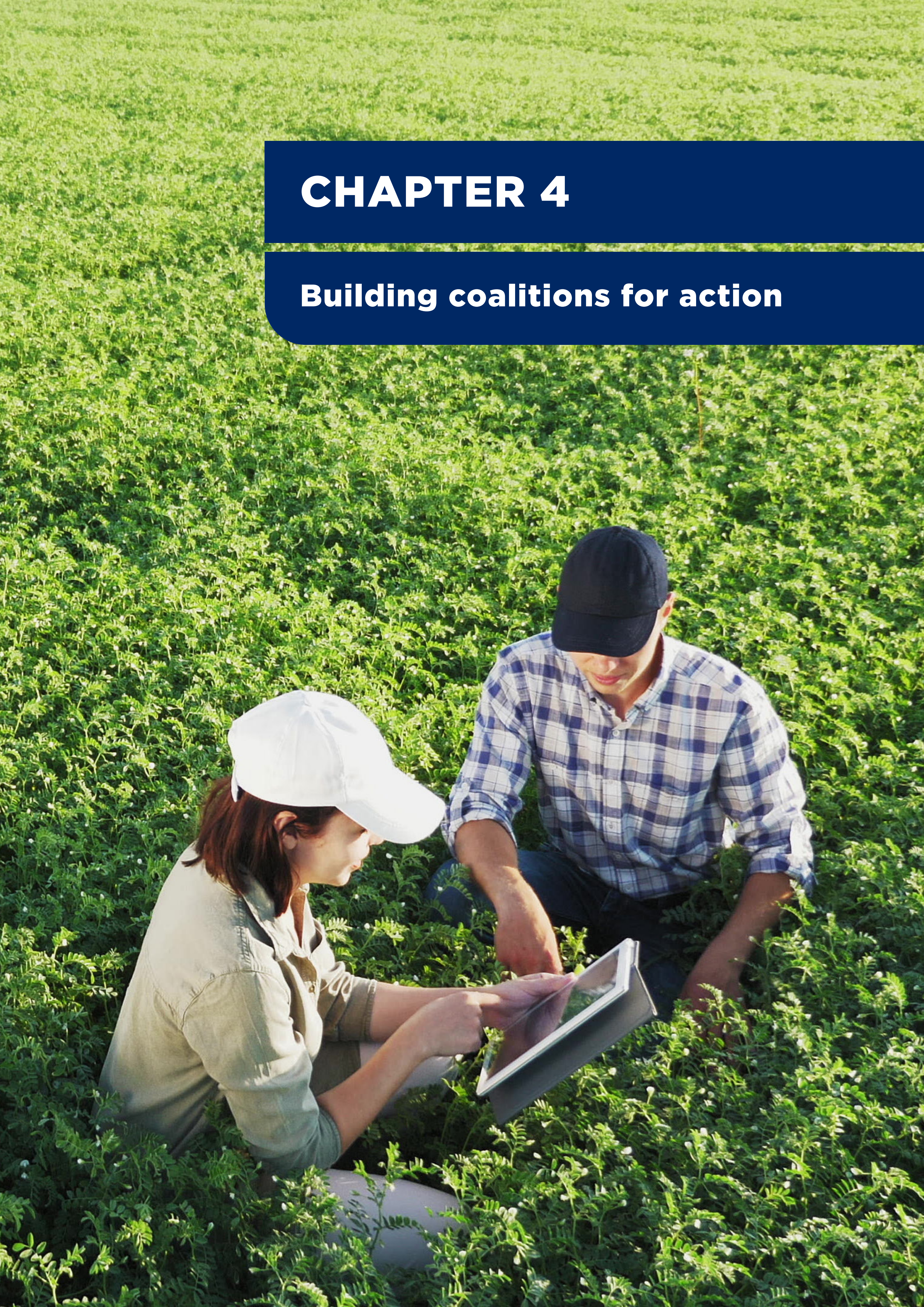
a. Does not include all carbon dioxide removal activities and methodologies. Some emissions reductions approaches may also be used to sequester carbon, e.g. through strategic fire management in the world's savanna regions.

b. The focus of this report is on the greenhouse gas emissions attributable to the use of mineral fertilizer and the carbon removals potential for soil that could neutralize the residual emissions from fertilizer use that cannot be abated. However, farmers, land managers and those setting and updating Nationally Determined Contributions (NDCs) need to consider the full lifecycle analysis of all emissions from agronomic management (fertilizer use, energy for irrigation, methane emissions from rice etc.) compared to carbon dioxide removals from soil carbon sequestration. For example, Gao et al (2018) identify that in China total greenhouse gas (GHG) emissions are about 12 times larger than carbon uptake by soil sequestration.

Source: Gao, Bing et al. "Chinese cropping systems are a net source of greenhouse gases despite soil carbon sequestration." Global change biology vol. 24,12 (2018): 5590-5606. doi:10.1111/gcb.14425

c. There is overlap in these practices with what is commonly known as regenerative agricultural practices, to which integrated plant nutrient management is integral. IFA has adopted an industry position that "recognizes regenerative agriculture as one of the approaches that can restore and maintain soil health, reverse biodiversity loss and increase soil carbon sequestration".

d. Other nutrients play different roles to bolster SCS. For example, using silicate fertilizer leads to phytolith formation, which can occlude organic carbon and improve the sequestration effect of soil.



CHAPTER 4

Building coalitions for action

Farmers are key to addressing nitrous oxide emissions from mineral nitrogen fertilizer use: they have the most ability to affect emissions through the way they manage their farms. Fertilizer companies will need to work together and with other parts of the food system to promote the best practices required, support farmers to adopt changes, and influence the market to set a consistent set of commercial incentives in line with emissions reductions. Each fertilizer company should consider where it can have the biggest impact, depending on its place in the supply chain.

Key actions include:

- supplying tailored products, nutrient blends and enhanced fertilizer products;
- educating and incentivizing farm advisers, input retailers and farmers directly to make sustainable nutrient choices;
- pursuing in-house R&D, pre-competitive collaboration for innovation, and partnerships with research institutions;
- participating in nutrient stewardship collective outreach programmes;
- working with standard-setters to develop high-quality farm certifications and metrics, and carbon credits for nutrient management;
- supporting policies consistent with emissions reductions and advising policymakers on how to incentivize and implement them;
- building relationships and coalitions for emissions reductions along the distribution chain; and
- partnering with food companies and retailers to reward farmers for making changes to practices.

The fertilizer sector should reflect on these proposals, make commitment by the time of the United Nations COP27 climate summit in November 2022, participate in the emerging Sectoral Decarbonization Approach and set science-based targets. The sector should press ahead with implementation to be able to present emerging results at COP28 in 2023.

Farmers are key players in addressing greenhouse gas emissions from mineral nitrogen fertilizer use, but may face barriers to change

1. Farmers are crucial to addressing greenhouse gas emissions from fertilizer use. They decide how products are applied, what products are applied and what crops are grown – all key factors in how much greenhouse gas is emitted as a result of mineral nitrogen fertilizer use.

2. The analysis in Chapter 2 identified that many of the measures to reduce emissions would be cost saving for farmers, and many farmers have indeed adopted best management practices, thereby bringing down emissions on their land. However, this is not the case on much of the world's agricultural land, with many areas seeing inefficient fertilization, despite the potential business advantages of improving efficiency.

3. Farmers may face barriers to adopting these measures, many of which may be outside their direct control. Among the most prevalent barriers are:

- lack of knowledge or resources to apply best management practices or to access certification schemes that could unlock additional revenues;
- financial barriers to accessing the required technology;
- constrained local labour markets restricting access to the workers required for more labour-intensive practices;
- lack of alignment between commercial advice and best management practices for emissions minimization;
- lack of support from peer networks; and
- lack of interest in downstream purchasers and off-takers in paying a price premium for low emission practices, or access to markets where they would pay such a premium.[239]

Fertilizer companies can help farmers to overcome these barriers

4. Many fertilizer companies already do significant work with farmers to help them overcome these barriers, both independently and by working with partners. However, they will need to do more to achieve the emissions reductions identified in Chapter 2.

5. Fertilizer companies need to consider their best routes to help farmers, depending on their position in the fertilizer supply chain, products and which markets they operate in.

6. Many initiatives will require collaboration with different parts of the value chain: with farmers directly, agronomic advisers, farm suppliers, food buyers, policymakers and others. Collaborating in this way will help to ensure that the business environment for farmers is consistent and conducive to change.

Fertilizer companies have several different routes into helping create a supportive environment for change

7. Figure 1 illustrates some of the key influences on farm business decisions and how fertilizer companies may be able to work with farmers and the wider ecosystem to shift the food value chain to a lower emissions model.

The market

8. The first key influence on farmers is the market. Farmers' business decisions will be in no small part driven by the prices they expect to receive for the crop when it is finally harvested and the cost of the inputs that crop requires. These output price expectations will be influenced by what crops off-takers are looking for, which in turn depends on what food companies, retailers and consumers are looking to buy.

9. On the input side, farmers' decisions will be affected by the price of the inputs, as well as agronomic advice they may receive independently from other farmers, government extension services or through the retailer, and their attitudes to risk. This applies both to decisions for this season and to longer-term capital investment decisions. In some cases, they may even buy advice, inputs and access to machinery bundled together as a service.

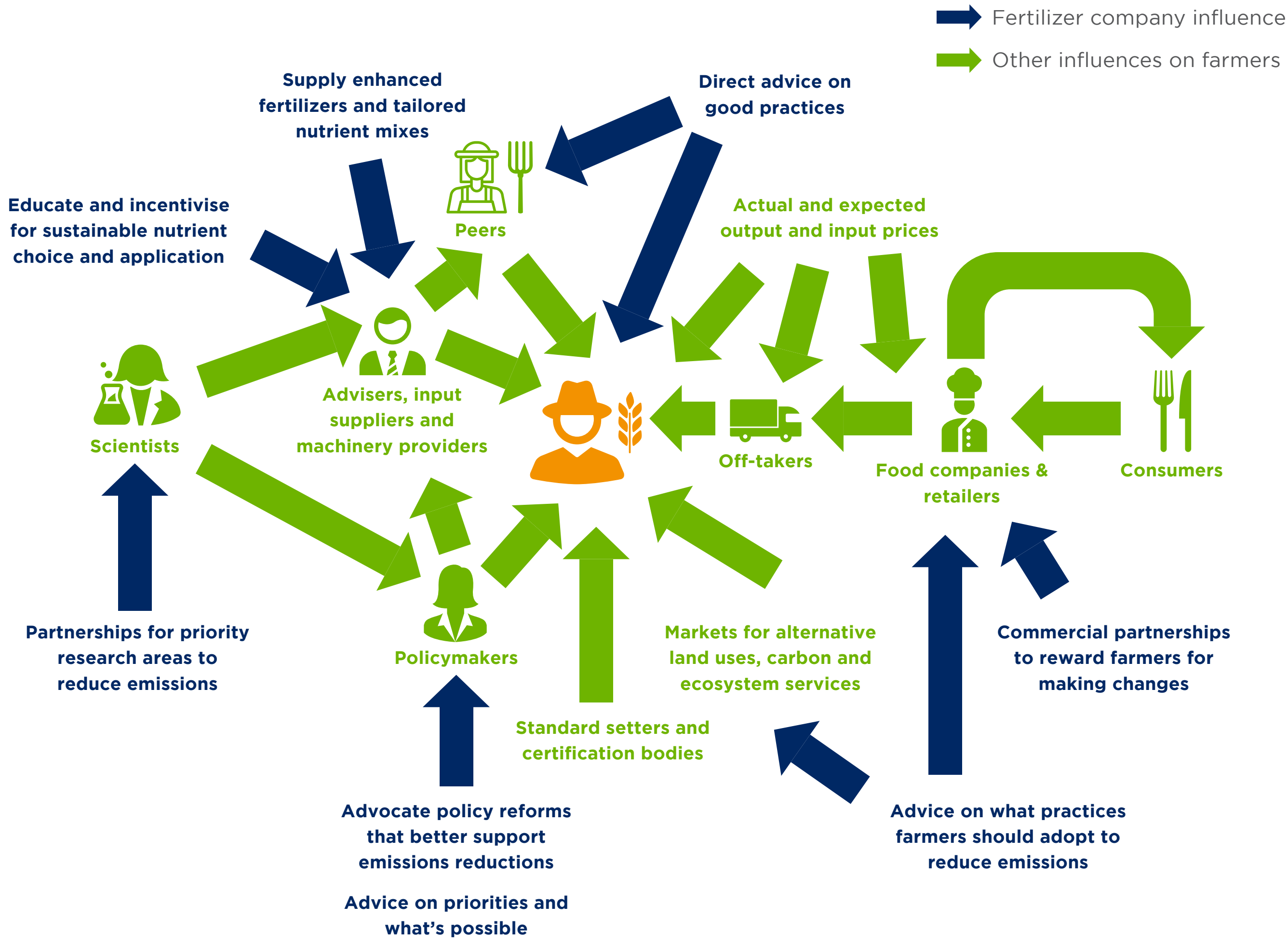
10. Further price signals come from the wider land-market. A farmer could choose to switch out of crop production entirely if returns are deemed too low: they could switch to grassland and livestock, plant trees for carbon credits, install solar cells or other infrastructure, or sell the land to another farmer or to developers. They could also choose to rent the land out to someone else, who may make a different management decision.

11. Emerging environmental markets provide a further price signal to farmers. Opportunities from the sale of carbon credits and other ecosystem services will increasingly influence how farmers manage their land, including which crops to plant in which location, which technologies to use and how much inputs to apply.

Peers

12. Farmers are also often heavily influenced by their peers.[240] What neighbouring farmers are growing and what practices they adopt can have a strong impact on what decisions a farmer takes: seeing the results of techniques applied on a neighbouring farm reduces the risk from adopting the change on a farmer's own farm. Peer networks can be very important for sharing knowledge, but also capital resources are required to optimize input. Fellow farmers may also be more trusted than other sources of information. Increasingly, these interactions can take place via social media, with online communities of practice and farming influencers providing information on what is happening on their farms.

Figure 1. Farmer decision-making and routes to influence



Public policy

13. Policymakers set regulatory standards, subsidies and taxes for farmers to try to achieve certain public policy goals such as environmental protection, reducing income inequality between farmers and the rest of society, or addressing failures in agricultural markets. This can shift a farmer's expected returns from a particular business decision, nudging decisions to align more closely with the public policy objective. Standard-setting and certification bodies can play a similar role, potentially unlocking higher value markets for farmers.

Science

14. Scientists have the potential to play a key role in determining the basis on which agronomists advise farmers and how policymakers pull their policy levers to achieve public policy outcomes. This is a very important part of the system but acts with a lag: it can take time for agricultural college curriculums to be updated or for new findings and recommendations to filter through the agronomic profession to become mainstream. This could particularly be the case if the latest science is not aligned with commercial incentives. In some cases, the links between scientists and industry can be weak, further delaying the impact of the latest findings.

The right routes to focus on will depend on each fertilizer company's place in the supply chain

15. Fertilizer companies will need to consider their place in the supply chain and local market characteristics in determining how best to support farmers to reduce emissions.

16. Some of these actions fertilizer companies can do alone. Others will require pre-competitive collaboration across the sector or with the wider food value chain. These are illustrated in Figure 2. Box 1 and Box 2 illustrate how these proposals could work in some of the systems discussed in Chapter 2.

17. All the measures should help to reduce greenhouse gas emissions. Some of the measures will count towards Scope 3 reductions, whereas others will be counted as beyond value chain mitigation, as set out in Chapter 2. Measures with more diffuse or long-term and uncertain impacts, such as R&D, may not be counted immediately.

Figure 2. Actions for fertilizer companies to address emissions alone and in coalition

<table>
<tr><th></th><th>Fertilizer manufacturer</th><th>Fertilizer traders and blenders</th><th>Fertilizer sellers</th></tr>
<tr><td rowspan="6">Individual companies</td><td colspan="3">Improve understanding of the distribution chain</td></tr>
<tr><td></td><td></td><td>Educate and incentivise advisers, input suppliers and machinery providers for sustainable nutrient choices</td></tr>
<tr><td></td><td></td><td>Advise farmers on good practices</td></tr>
<tr><td>Supply enhanced fertilizer products</td><td></td><td></td></tr>
<tr><td colspan="2">Supply tailored nutrient blends</td><td></td></tr>
<tr><td colspan="3">In-house R&D</td></tr>
<tr><td rowspan="3">Fertilizer sector together</td><td colspan="3">Nutrient stewardship collective outreach programmes</td></tr>
<tr><td colspan="3">Pre-competitive innovation initiatives (e.g., challenge prizes)</td></tr>
<tr><td colspan="3">Work with standard setters to develop high quality farm certification criteria and robust evidence bases for carbon credit issuance for nutrient management</td></tr>
<tr><td rowspan="3">In coalition with the food chain and policy makers</td><td colspan="3">Form partnerships with research institutions to influence priority areas for research</td></tr>
<tr><td colspan="3">Commercial partnerships with and advice for food companies to reward farmers for making changes to practices
Commercial incentives for farmers to adopt best fertilizer and wider farm management practices</td></tr>
<tr><td colspan="3">Advocate policy reforms that better support emissions reductions
Advise policymakers on priorities and what is possible</td></tr>
</table>

Box 1. How the scientific research community, agribusiness and government collaborated with farmers in China to reduce fertilizer overuse

China set out a formal policy to deliver zero growth in the use of mineral fertilizer in 2015, but absolute usage of mineral nitrogen fertilizer had already been declining since 2013. By 2020, levels had reached those similar to 2004.[241] At the same time, China has been pursuing a long-term goal of food self-sufficiency,[242] so how were policymakers convinced to tackle mineral fertilizer overuse without jeopardizing this?

This success was partly thanks to the efforts of the scientific community who, through a systematic study over 10 years between 2005 and 2015, engaged with up to 21 million farmers in the country to help them increase their yields while still reducing their use of fertilizer. Farmers saw the economic benefit of this, with those involved in the project being cumulatively US$21 billion better off.[243]

Field studies were used across the country in major row crops (maize, rice and wheat) to assess crop varieties, planting times and densities, and fertilizer and water use. Using data from these field trials, evidence-based advice was given to farmers that was optimized for their local conditions. Recommendations included reducing absolute nitrogen application rates in some crop systems by 20% but increasing the rate applied at different points in the growing season. With the number of farmers taking up these recommendations, the programme was able to save 1.2 Mt N China.

The key success of the programme was the outreach and engagement strategy to convince millions of smallholder farmers to change and adopt these best practices. A core network of around 1,000 scientific researchers worked with c. 65,000 extension agents and 140,000 agribusiness employees across the country to run outreach programmes and workshops with farmers, highlighting the importance of social networks and social influence among other factors.

Initiatives on this scale may not be achievable in countries with a less centrally controlled government or with smaller populations, and it should be noted that 21 million farmers are still only a small proportion of total farmers in China. Likewise, the circumstance of millions of smallholders with access to ample mineral fertilizer and therefore high levels of overuse is not applicable everywhere, when many farmers in low-income countries have excessively high levels of nitrogen use efficiency, indicating nutrient mining driven by lack of mineral fertilizer.[244] However, it does demonstrate that with the right scientific, localized optimization recommendations combined with the reach and collaboration of the public and private sector, farmers can be persuaded to adopt changes for both their own economic benefit and for the environment and wider society.

Actions for individual fertilizer companies

Supplying tailored products, nutrient blends and enhanced fertilizer products

18. Practising balanced nutrition, and considering use of enhanced fertilizer products such as controlled-release fertilizers and nitrification and urease inhibitors, where appropriate, have potential to help bring down emissions.

19. Fertilizer companies should develop and promote products and blends optimized to minimize emissions and support soil carbon sequestration (SCS), according to different climate conditions, soil types and crops.

20. Fertilizer companies and their distributors should continue to ensure that the nutrient mixes they offer are precisely tailored to the site- and crop-specific needs in the various markets they supply.

21. They should work to improve the applicability, availability and take-up of enhanced fertilizers, and ensure distribution chains have the incentives and expertise to sell these products. Companies need to address price barriers to product adoption, and tackle questions about the wider environmental impacts of such products. This is discussed in the R&D section below.

22. Finally, they should provide an adequate supply of products for use in precision agriculture to help facilitate these technologies' adoption and so support improvements in nitrogen use efficiency (NUE).

Educating and incentivizing farm advisers, input retailers and farmers to make sustainable nutrient choices

23. Agronomic advisers and farm suppliers are an important source of advice for farmers in some markets. This advice can be bundled with other services, such as applying the product (a fertilizer-as-a-service model), farm machinery sales or rental, or farm management software, among others.

24. These advisers and suppliers can be powerful intermediaries in supporting improved adoption of climate-friendly practices,[245] but the incentives for advisers and farm suppliers may not always support emissions reductions. They may receive commission on sales (or will at least profit from the sale), which may lead them to recommend more mineral fertilizer than may be necessary.

25. On the other hand, advisers and farm suppliers also need to demonstrate to their farmer customers that they are helping them achieve their business objectives, tempering any incentives to oversupply fertilizer in a way that would harm customers' profitability. This would tend to push NUE to a reasonably high level where it is profitable to do so. However, actions to reduce emissions further may incur additional costs that would not be associated with improved yield, leading to an adviser recommending against such actions.

26. Fertilizer companies can help to shift the incentives on farm suppliers and advisers to support incorporation of advice on sustainability into standard recommendations for farmers. Actions could include:

- scaling up efforts to ensure that fertilizer companies' distributors and network of farm advisers have the expertise and incentives to take climate impacts into account in their recommendations to farmers;
- incorporating climate impacts into the algorithms and online tools for determining optimal application rates, and refining such tools to consistently include, for example, medium-term weather forecasts to better balance yield with likely greenhouse gas emissions;
- shifting away from sales fees focused on volumes and towards building long-term advisory relationships, or even formally separating advice from sales; and
- lobbying for policymakers to require such separation of advice and sales across the industry.

27. This needs to be done carefully. Farmers may choose to change adviser if they perceive the adviser is not supporting their business interests. This means that fertilizer companies and advisers need to provide extra support to farmers to build the case for incorporating climate impacts into business practice. Notwithstanding this, many farmers take their role as stewards of the land very seriously and will already look to moderate short-term business decisions to support climate and environmental action both globally and locally.

Box 2. Emissions reductions in France

The farm cooperative network is a significant source of advice and input for farmers in France. It is therefore likely to be an important vehicle for fertilizer companies looking to shape the incentives for farmers.

The cooperative VIVESCIA has reported that low-carbon grains are in demand both from its own downstream processing operations and its major food-processing customers. It has launched a tool to help its members understand their carbon footprints, and has organized a series of awareness-raising meetings for farmers to tackle some of the misconceptions around agriculture and climate change and help farmers understand how to reduce their carbon footprints. VIVESCIA is also collaborating with Malteurope and Heineken to reduce the emissions from barley production.[246] Fertilizer companies could support this process, providing advice and scientific input on best management practices to further drive down emissions.

The wider regulatory regime for farmers is also likely to create increased pressure on farmers for improved fertilizer management. Fertilizer companies should seek to ensure government efforts are aligned with best practice for reducing greenhouse gas emissions. France's Climate Law 2021 includes a target for a 15% reduction in nitrous oxide emissions from agriculture by 2030 from a 2015 baseline. The law requires the creation of a national emissions-reduction plan, and provides for a levy on the use of mineral nitrogen fertilizer if the target trajectory is not met for two consecutive years.[247] This is an opportunity for fertilizer companies to work with French policymakers to ensure the emissions reduction plan aligns fully with best management practices to meet this target as efficiently as possible.

Further policy pressure is coming from the European level. The European Green Deal includes a commitment to reduce nutrient losses by 50%, while ensuring no loss of soil fertility. The European Commission believes this will reduce the use of fertilizers by at least 20% by 2030. Fertilizer companies can use this as an opportunity to help farmers to use mineral fertilizer more efficiently to comply with the requirements under this target, while also maintaining yields and soil health.

Actions for the fertilizer sector together

Pursuing in-house R&D, pre-competitive collaboration for innovation, and partnerships with research institutions

28. There have been few breakthroughs in mineral fertilizer since the development of the Haber-Bosch process in the early 20th century. Addressing the challenge of decarbonization will require both improved understanding of how and when nitrous oxide emissions arise and the technologies that can help to mitigate these emissions, while continuing to provide the required nutrition to plants.

29. There is a possibility that policymakers restrict use of some existing technologies to try to address other environmental issues. The UK government consulted on restricting urea use to help improve air quality.[248] The European Chemicals Agency has proposed banning the addition of microplastics to fertilizers, a key feature of many controlled-release fertilizers.[249] And the European Commission has called for further regulatory risk management measures for pyrazoles, a component of some nitrification inhibitors.[250]

30. Fertilizer companies need answers to these challenges to feed into a long-term strategy for providing crop nutrition. A key source of solutions will be through increased R&D activity. This could span:

- improving understanding of existing best management practices to minimize emissions and refining decision tools for different contexts;
- improving existing products and making them affordable for large-scale use, including controlled-release and stabilized fertilizers, increasing their efficiency. Also, looking to better understand and to address any wider environmental impacts, for example through new, fully biodegradable coatings;
- research into novel, smart fertilizer products or technologies that could have low-

er emissions combined with high efficiency and biodegradability; this could include new fertilizer formulations (modes of action) or microbial amendments that provide new ways of delivering nutrients to plants, triggered by plant roots;

- improving the efficiency with which crops take up and convert nutrients into harvested products or soil carbon, for example through breeding varieties with more extensive root systems or improved photosynthesis or increased nutrient harvest index, or through the use of biostimulants; and
- reducing the cost and increasing the accuracy and scalability of technologies for measuring nitrous oxide emissions and SCS; this would help improve understanding of different measures' impacts on emissions.

31. Some of these areas of research have been under way for some time and have not yet reached commercial viability, while others are more innovative and will take many years before commercial release. Nano urea is an example of an emerging technology that has potential to enhance crop yields and reduce nutrient losses through nanotechnology, with some initial commercialization in India to date.[251] However, further research is needed to understand its mode of action, optimal usage and potential benefits to improved NUE and reduced greenhouse gas emissions.[252]

32. Fertilizer companies would be able to do some of this research in-house, but other areas will require external expertise in wider areas of science and collaboration in more open innovation settings. Some areas could be proprietary product-related knowledge for individual fertilizer companies. Other areas will require more fundamental research that could not be supported by any individual company and could bring wider benefits to society as a whole. Some R&D work might also take place in sister industries, such as the life science industry for microbials and biostimulants, which will require developing partnerships across industries.

33. To deliver the research areas that cannot be done in-house, there are three important models:

- **Sectoral competitions:** Fertilizer industry-specific research could be supported through sector-wide pre-competitive initiatives such as innovation competitions. Acting on behalf of the sector, the International Fertilizer Association, or similar body, could offer a prize for developing a new technology or breakthrough in a specific area, or coming up with a solution to a defined problem. For example, the Homegrown Innovation Challenge is offering a CA$33 million prize for teams that enable Canadian farmers and producers to produce sustainable, competitive berries out of season;[253]
- **Partnerships and investment in start-ups:** Fertilizer companies can provide finance, facilities and technical support for innovative start-ups. This can give the fertilizer company privileged commercial access to emerging ideas and expertise that they may not have in-house; and
- **Partnerships with other institutions:** Partnerships with other companies and institutions could allow sharing of expertise and resources across different industries. In some areas, more fundamental research may be required, perhaps requiring extended partnerships with universities and public research institutions. Fertilizer companies can support public research funders in understanding the emissions-saving potential of improving scientific knowledge around soil nutrition and the areas of focus. By providing co-funding, the sector can help policymakers to justify the investment and amplify the potential impact of public funds.

Nutrient stewardship collective outreach programmes

34. One of the challenges for fertilizer companies looking to address in-field emissions from fertilizer use is the complexity of the fertilizer distribution chain, as described in this report. This can make it hard for companies to identify where their product is used, and so to address emissions from its use.

35. One way to try to overcome this barrier is for fertilizer companies to come together to establish a central fund for advisory and information services. It could also include more innovative outreach programmes working with social media influencers who are farmers or working on agricultural issues.

36. This centralized service would ensure that farmers have access to a common set of information, avoiding any contradiction. It avoids potential freeriding, where one fertilizer company benefits from reduced Scope 3 emissions as a result of another company's outreach efforts. At the same time, it gives companies confidence that their efforts will result in reductions to the emissions from their own products. Separating advice from any individual company also removes incentives for the advisers to push for more than necessary mineral fertilizer use. Fund administrators would have targets for improved NUE that are consistent with the trajectory required under a future Sectoral Decarbonization Approach, with associated responsibility for data improvements.

37. Fertilizer companies have already come together to deliver initiatives like the 4R Nutrient Stewardship, which disseminates information and training on best practices,[254] but a more extensive programme of work with farmers might be able to increase the impact further, especially where NUE is still low.

38. Such a model could draw inspiration from extended producer responsibility systems seen in the plastics sector. This sector also has to address environmental impacts of their products when they do not always have good information about where their products go or how consumers dispose of them. The fixed costs of addressing the problem are also high. To address this, companies that sell plastic packaging pay into a central fund that supports waste collection, processing and recycling or disposal of the product. The administrator of the fund is then required to achieve certain recycling targets. Through this mechanism, the industry can reduce its environmental impact in a cost-effective manner.[255]

39. In the agriculture sector, statutory bodies such as the Grains Research and Development Corporation (GRDC) in Australia could also offer a parallel. The GRDC is funded by a combination of compulsory levies on grain growers and government grants. Its role is to invest in R&D and extension services to ensure the enduring profitability of Australian grain growers.[256]

Working with standard-setters to develop high-quality farm certifications and metrics, and carbon credits for nutrient management

40. Certification of farms that meet specified standards is one way that farmers can try to unlock higher value for their products, thereby financing improved sustainability. Nutrient management does not consistently appear in these standards, or at least not in sufficient detail to drive change. Fertilizer companies can support these standard-setters in developing robust criteria for responsible nutrient management and greenhouse gas emissions minimization.

41. Fertilizer companies should also work with measurement, reporting and verification bodies for SCS to ensure robust incorporation of the latest science on best practices and to improve the accessibility of the standards for farmers.

42. These efforts can help to support market transparency for the sector's emissions, develop carbon farming and ensure a high-integrity carbon market.

Supporting policies consistent with emissions reductions and advising policymakers on how to incentivize and implement them

43. Public policy – regulations, taxes, subsidies, non-statutory guidance – has an important role in influencing the business incentives farmers face. These policies are often developed and accumulate over extended periods, and so can reflect past political priorities that can be less relevant or even in conflict with today's objectives. Nevertheless, reform can be politically difficult to deliver and needs to be very carefully managed, given the potentially significant impacts on large numbers of people's livelihoods.

44. Some jurisdictions offer farmers subsidized fertilizer, for example. The rationale for such subsidies was to incentivize adoption to boost yields and the food supply.[257] However, there is now evidence that these subsidies may encourage imbalanced and inefficient fertilizer use,[258] with associated greenhouse gas emissions. Reforming and refocusing obsolete subsidies and wider public policies could help to improve incentives for good farm practices, and can be achieved in ways that protect the incomes of the individuals affected through the transition either directly[259] or through boosting farm productivity[260] or diversification.[261]

45. This report does not explore local policy options in detail, but reformed policy frameworks could focus subsidies on the adoption of best management practices, or could regulate to require their adoption. The French government requires use of a balance sheet method, including regular soil testing, for calculating nitrogen fertilizer rates as part of its implementation of the Nitrates Directive.[262] The UK government's new Sustainable Farming Incentive in England will include payments to help minimize greenhouse gas emissions from fertilizer use, including through the use of precision agricultural tools and whole-farm nutrient budgeting.[263] And the Canadian province of Alberta's carbon offset market allows farmers to generate carbon offsets through implementation of a 4R nitrogen stewardship plan on agricultural land.[264]

46. Fertilizer companies should enhance their engagement with policy development processes, including meeting policymakers and politicians and publicizing information and research in support of efforts to reduce emissions. This will help to ensure that governments have a strong understanding of the impacts of inefficient mineral fertilizer misuse and the kinds of changes that can be possible. This will help to shift political priorities in favour of emissions reductions. Such efforts will be particularly powerful where increasing efficiency would be win–win, saving money for farmers and the government budget, while also improving yields and minimizing the carbon footprint.

In coalition with the value chain, food system and policymakers

Building relationships and coalitions for emissions reductions along the distribution chain

47. Fertilizer companies should build relationships and coalitions for emissions reductions along the distribution chain.

48. The distribution chain for mineral fertilizer includes mixing of products and trading between fertilizer manufacturers, blenders and retailers. This can make it difficult to identify where a company's product is used, and so where to prioritize action.

49 An important step in building a programme for reducing a company's Scope 3 emissions will be to strengthen relationships and develop coalitions for emissions reductions along the distribution chain. This will help to improve understanding of how fertilizer is used and where there are gaps.

Partnering with food companies and retailers to reward farmers for making changes to practices

50. In common with the fertilizer sector, downstream food companies and retailers are experiencing investor and consumer pressure to address greenhouse gas emissions and environmental impacts across their supply chains and have made commensurate commitments to decarbonize.[265] This creates a common interest with the fertilizer sector in supporting farmers to reduce emissions.

51. Food companies and retailers can set minimum standards on the inputs they buy. In the past these have focused on food quality, but can also be linked to production method. These can be determined in different ways: outcome based, such as a particular carbon footprint; associated with a points system, such as requiring a particular score on the Farm Sustainability Assessment; or process based, such as adherence to the practices required by GlobalGAP.

52. As a minimum, the fertilizer sector can ensure food companies and retailers have good information on what standards they should set for mineral fertilizer use. This will ensure a single set of advice to farmers from both ends of the supply chain.

53. Going further, fertilizer companies could collaborate with food companies to try to unlock consumer value, and so value for farmers, from low-carbon food production. Such a standard would stretch from mineral fertilizer production through to the final product on the shelves of a food retailer. Ultimately, environmental stewardship goes far beyond the specifics of mineral fertilizer use. It means responsible, evidence-based farm management practices to improve soil health and soil organic carbon, and to further reduce nitrous oxide emissions through actions such as changes to crop rotations.

GLOSSARY OF TERMS

4R Nutrient Stewardship – Four areas of nutrient management (source, rate, time and place) that provide the basis of a science-based framework for the efficient and effective use of plant nutrients.

Agriculture, Forestry and Land Use (AFOLU) – Term used by the IPCC that describes the anthropogenic greenhouse gas emissions from Agriculture and LULUCF (Land Use, Land Use Change and Forestry).

Carbon dioxide equivalent (CO_2e) – A carbon dioxide-equivalent, abbreviated as CO_2e, is a measure used to aggregate and compare emissions from various greenhouse gases on the basis of their different global-warming potentials (GWP). Quantities of each gas are converted to the equivalent amount of carbon dioxide based on the same global warming potential over a defined time period. For example, the GWP for methane is 25 and for nitrous oxide 298. This means that the global warming impact of emissions of 1 Mt of methane and nitrous oxide respectively are equivalent to emissions of 25 and 298 Mt of carbon dioxide over a 100-year time horizon.

Carbon dioxide removal (CDR) – Sometimes shortened to 'carbon removals' refers to actions such as soil carbon sequestration that can result in a net removal of CO_2 from the atmosphere.

Controlled-release fertilizer – A fertilizer product that releases nutrients at a controlled rate relative to a "reference soluble" product. The controlled rate of nutrient release is achieved by modifying readily available nutrient forms with recognized physical mechanisms such as coatings, occlusions or other similar means.

Farm-gate – Relating to processes and outputs that originate and conclude on the farm.

Greenhouse Gas Protocol – Establishes comprehensive global standardized frameworks to measure and manage greenhouse gas emissions from private and public sector operations, value chains and mitigation actions.

Inhibitors – Urease inhibitors are compounds that inhibit hydrolytic action on urea by the urease enzyme. This helps to slow ammonia volatilization, which is a potential source of air and water pollution and an indirect source of nitrous oxide.

Nitrification inhibitors are compounds that that inhibit the biological oxidation of ammoniacal-N to nitrate-N by the bacteria responsible for converting ammonium to nitrite (nitrosomonas) and nitrite to nitrate (nitrobacter). These compounds protect against both denitrification and nitrate leaching losses.

Urease and nitrification inhibitors break down over time. The rate of breakdown is influenced particularly by temperature, and these products generally remain effective longer at cooler soil temperatures, with efficacy ranging from two to several weeks.

Measurement, reporting, and verification (MRV) – The practice of "MRV," which integrates three independent, but related, processes of measurement or monitoring (data and information on emissions, mitigation actions, and support), reporting (compiling the information in inventories and other standardized formats), and verification (subjecting the reported information to some form of review or analysis or independent assessment).

Neutralization – Measures that companies take to remove carbon from the atmosphere and permanently store it to counterbalance the impact of emissions that remain unabated.

Nitrogen Use Efficiency (NUE) – NUE is defined here as the ratio of the quantity of nitrogen removed from a given area during harvest and the total amount of nitrogen that enters that area. Nitrogen inputs include mineral and organic fertilizer, biological nitrogen fixation and atmospheric deposition. An optimal level of NUE (e.g., about 70-80% in cereal systems) represents high crop productivity, minimum risk of nitrogen surpluses and the consequent environmental impacts and no depletion of soil nitrogen resources.

Scope 1, 2, 3 emissions – As defined by the Greenhouse Gas Protocol, Scope 1 emissions are from the direct emissions from a reporting company, Scope 2 are indirect emissions from purchased energy, and Scope 3 are indirect emissions in both the upstream and downstream activities and value chain of the reporting company.

Slow-and controlled-release fertilizer – A fertilizer product that releases (converts to a plant-available form) its nutrients at a slower rate relative to a "reference soluble" product. This may be accomplished by biological activity and/or by limited solubility and/or by hydrolysis or other recognized chemical or biochemical means.

Tiers 1, 2, 3 (in context of IPCC) – These tiers represent a level of methodological complexity. Tier 1 is the basic method, Tier 2 intermediate and Tier 3 the most demanding in terms of complexity and data requirements.

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Reducing Emissions from Fertilizer Use examines the opportunities to reduce Scope 3 emissions from the use of fertilizers in agriculture and to support the removal of carbon from the atmosphere through soil carbon sequestration. The fertilizer industry is looking to address these emissions, playing its part in keeping to the Paris Agreement's 1.5°C goal, while ensuring the continued supply of fertilizers required by farmers to ensure the world's ability to feed a growing population.

This document is a publication from Systemiq, commissioned by the International Fertilizer Association (IFA) and funded by nine IFA members. The report was prepared by Systemiq in close consultation with and technical input from IFA and the sponsoring companies, as well as discussions with academia and civil society.

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