Greenhouse gas emissions from nitrogen fertilisers could be reduced by up to one-fifth of current levels by 2050 with combined interventions

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Abstract:

Food security relies on nitrogen fertilisers, but its production and use account for approximately 5% of global greenhouse gas (GHG) emissions. Meeting climate change targets requires the identification and prioritisation of interventions across the whole lifecycle of fertilisers. Here, we have mapped the global flows of synthetic nitrogen fertilisers and manure, and their corresponding GHG emissions across their lifecycle. We have then explored the maximum mitigation potential of various interventions to reduce emissions by 2050. We found that approximately two thirds of fertiliser emissions take place after their deployment in croplands. Increasing nitrogen use efficiency is the single most effective strategy to reduce emissions. Yet, this should be combined with decarbonisation of fertiliser production. Using currently available technologies, GHG emissions of fertilisers could be reduced up to approximately one fifth of current levels by 2050.

Introduction

The global population is expected to grow by more than 20% until 2050[1], at the same time when GHG emissions need to be substantially reduced to avert the gravest consequences of climate change. Yet, most food production relies on the use of manure and synthetic nitrogen fertilisers, whose production and use are estimated by this study to be responsible for approximately 5% of global emissions[2]. Its use is so widespread that Erisman *et al*. estimated that around 48% of the global population are fed with crops grown with synthetic nitrogen fertilisers[3,4]. Mitigating climate change while avoiding risks to food security is therefore a challenging endeavour that requires fast and scalable solutions.

There are four main sources of nitrogen inputs into crops: natural atmospheric deposition, biological nitrogen fixation, manure, and synthetic nitrogen fertilisers[4,5]. However, neither natural atmospheric deposition nor biological fixation alone generate enough nitrogen for the current required crop output, and for this reason both manure and fertilisers need to be deployed. Unfortunately, both the production and overuse of these alternative sources of nitrogen lead to a series of environmental challenges, including eutrophication, soil acidification, energy use, and GHG emissions[6,7]. Among all the challenges, reducing GHG emissions associated with nitrogen fertilisers would be an essential contribution to meet the 1.5 °C global warming target, while ensuring food security[8]. This is currently a share of global emissions of the same order of magnitude as the iron and steel industry (7% of the global emissions, and the largest global source of industrial emissions)[9], cement (6%)[9], and plastics (4%)[10].

Both the production and use of nitrogen fertilisers lead to the release of CO_2, N_2O and CH_4, which are among the most important global GHGs. The synthesis of ammonia, from which all synthetic fertilisers are produced, accounts alone for about 0.8% of the global GHG emissions[11] and 2% of global energy[12]. Natural gas, coal and oil are used as feedstock and fuels for the production of ammonia[13], and GHGs are released from the extraction and combustion of these fuels, but also as the product of chemical reactions. Additional emissions arise from the generation of electricity used to drive the compressors and pumps. N_2O, a greenhouse gas with a global warming potential 273 times greater than CO_2[14], is also released as a by-product in the production of nitric acid, which is a feedstock for several nitrogen fertilisers.

Further GHG emissions are generated when fertilisers are used. Most notably, N_2O is directly generated as a by-product of nitrification and denitrification processes of soil bacteria[15,16]. Besides, N_2O is indirectly released from nitrate leaching and ammonia volatilization, which are partially converted to N_2O later by bacteria in the soil[17]. Additionally, CO_2 is also produced during the decomposition of urea and ammonium bicarbonate (ABC) in the cropland, and as a result of the use of limestones to neutralise the soil acidification caused by nitrogen fertilisers[18].

The integrated assessment of GHG emissions at all stages of the lifecycle of nitrogen fertilisers is essential to identify and prioritise mitigation options. However, GHG emissions associated with the production and use of fertilisers are usually considered separately in the literature, probably because fertiliser syntheses are studied by chemical engineers while fertiliser application is investigated by agricultural scientists[19-22]. For the production of synthetic fertilisers, the IEA proposed a technology roadmap, combining water electrolysis, carbon capture and storage (CCS), biomass gasification and methane pyrolysis, to mitigate GHG emissions from the production of ammonia[12]. Furthermore, Fertilizers Europe also systematically investigated the GHG emission factors of the productions of all nitrogen fertilisers across all world regions[23].

Existing literature has also explored the emissions during the use of fertilisers. Emission factors in the use phase have been quantified by the IPCC[18]. Additionally, Zhang *et al*. have systematically investigated the GHG emissions across all lifecycle stages of fertilisers, although this was limited to China[24]. Similarly, Fertilizers Europe calculated the GHG emission factor from the production and use phase of each nitrogen fertiliser in Europe[25]. The global GHG emissions from manure has also been estimated by the FAO[26].

Various mitigation options at various lifecycle stages have been identified and their mitigation potential has been quantified in the literature. For the production of fertilisers, water electrolysis can be used to supply hydrogen for ammonia synthesis, thus avoiding GHG from steam methane reforming[12,27]. Alternatively, electric heating powered by non-emitting electricity can eliminate combustion emissions[28,29]. CCS can also be deployed to avoid the release of CO_2 emissions[20,30]. Additionally, novel catalysts have been adopted to reduce the nitrous oxide emission from the production of nitric acid in Europe[31].

For the use phase, nitrification inhibitors and urease inhibitors are proved to reduce N_2O emissions in the cropland[32]. Meta-analysis results quantified the effect of the mitigation options[33-35]. Moreover, it has been found that the amount of fertilisers used in croplands can be substantially reduced, as much more nitrogen is being supplied in fertilisers than the nitrogen absorbed by crops[4].

Existing literature provides compelling examples of how to mitigate GHG emissions from the production and use of synthesised nitrogen fertilisers. Yet, so far a global assessment of GHG emissions from nitrogen fertilisers has not been established. This can enable the prioritization of the mitigation potential of various interventions often only assessed in isolation in the literature.

In this paper, we fill this gap by mapping the GHG emissions from the production and use phase of synthesised nitrogen fertilisers and manure, and by quantifying the effects of various mitigation interventions.

Results

We have mapped the global flows of fertilisers and their emissions for 2019, along all stages of the lifecycle, by reconciling the production and consumption of nitrogen fertilisers and regional emission factors in nine world regions (more details can be found in the Methodology section and in the SI file). This is the basis for quantifying the maximum mitigation potential of various future interventions, and then an assessment of the sensitivity of the most important parameters that influence maximum mitigation potentials.

Current mass flow of nitrogen fertilisers and GHG emissions

Fig. 1 shows the global mass flow of nitrogen in synthetic fertilisers and manure in 2019 across all stages of the supply chain, including production and use, and the corresponding GHG emissions. It is estimated that a total of 2.6 Gt CO_2e a^{-1} are associated with the production and use of synthetic nitrogen fertilisers and manure. This corresponds to the production of 108.5 Mt N a^{-1} of synthetic nitrogen fertilisers and 123.8 Mt N a^{-1} of manure.

1.31 Gt CO_2e a^{-1} (95% confidence interval: 1.15-1.56 Gt CO_2e a^{-1}) are result from the production and use of synthetic fertilisers. Unlike many other products, only approximately a third of whole lifecycle emissions is released during production. The bulk of emissions are generated when fertilisers are used in croplands, owing to direct and indirect N_2O emissions and CO_2 emissions from limestone and the decomposition of urea and ABC. Our results on the global mass flow of synthetic nitrogen fertilisers are within 0.3% of the figure reported by the Food and Agriculture Organisation (FAO)[36], and estimated GHG emissions show good agreement with data reported by other disparate sources[36,37].

Emissions from the production of synthetic fertilisers arise mostly (84%) from ammonia synthesis, partially (21%) due to chemical reactions used in the production process. These are the net process emissions (103 Mt CO_2e a^{-1}), because some of the CO_2 generated during ammonia synthesis is used as a feedstock for the production of urea and ABC. Further 85 Mt CO_2e a^{-1} as N_2O are emitted as a by-product from the production of nitric acid. While Fig. 1 depicts the global flows, the breakdown of total GHG emissions and types of fertilisers across nine different world regions is shown in Section 3 of the SI.

The bottom of Fig. 1 shows the global mass flow of manure and corresponding GHG emissions in 2019, estimated from the heads of animals reported by the FAO[26], and as recommended by the IPCC[38]. The global production amounts to 123.8 Mt N a^{-1} of manure and 4.3 Mt N a^{-1} bedding materials, but only around 43% is applied to soils as a fertiliser. 41% of manure is left on the pasture, and the remaining 16% is wasted in the manure management process. Both N_2O (3.3 Mt N_2O a^{-1}, equivalent to 908 Mt CO_2e a^{-1}) and methane (13.5 Mt a^{-1}, equivalent to 364 Mt CO_2e a^{-1}) are emitted in the manure management and use, resulting in a total of 1.27 Gt CO_2e a^{-1} GHGs from manure. On average, 23 t CO_2e/t N is released from manure applied to the soils, being this 1.9 times the average emission factor of synthetic fertilisers. GHG emissions from manure across various world regions, animals and lifecycle stages are provided in Section 3 of the SI.

Mitigation options

Although the results of Fig. 1 show the annual flows of fertilisers for only one year, 2019, this assessment enabled the mapping of all sources of GHG emissions along the supply chain, and this could then be used to anticipate future emissions for alternative interventions. This is shown in Fig. 2a for various alternative isolated interventions. For example, using the forecasted global demand for synthetic fertilisers by the FAO[36,39], 135.7 Mt N a^{-1} in 2050, we estimate that this would involve 1.66 Gt CO_2e a^{-1} (95% confidence interval: 1.44-1.99 Gt CO_2e a^{-1}) if the composition of demanded fertilisers, their production processes and use practices remain the same as in 2019. We call this our business as usual (BAU) baseline scenario.

Since both the production and the use of fertilisers are responsible for GHG emissions, mitigation interventions should target these two distinct stages of the lifecycle of fertilisers. For this reason, various interventions were selected from the literature as having high technology readiness levels, and their maximum mitigation potential was estimated. These are briefly described in this section, but full details are provided in Section 2 of the SI file, where the full comparison of mitigation interventions in the production and use phases is presented in Table S4 and Table S5, respectively.

Most of production emissions arise from ammonia synthesis, whose feedstocks are hydrogen and nitrogen. While nitrogen can be separated from air driven by zero-emissions electricity, water electrolysis powered by renewables can be used to produce hydrogen with low emissions. Process heat that is currently provided by fossil fuel combustion could be replaced by electric heating powered by renewables. The maximum mitigation potential of these interventions is explored in our first scenario (water electrolysis scenario in Fig. 2a).

Alternatively, hydrogen for ammonia synthesis could continue to be obtained by steam methane reforming and coal gasification, but emissions could be reduced by deploying electric heating thus avoiding fossil fuel combustion for process heat[40]. This option is explored in our second scenario (electric heating scenario in Fig. 2a). Additionally, CCS could be deployed to existing steam methane reforming, coal gasification, and boilers to capture CO_2 streams. This intervention is explored in our third scenario (CCS scenario in Fig. 2a).

For the use phase, the maximum mitigation potential of three interventions is also quantified. These interventions explore the impacts of reducing demand for fertilisers, reducing the N_2O emissions by deploying nitrification inhibitors, and changing the mix of fertiliser types.

Currently the nitrogen input to croplands, either as artificially or by natural processes, is much greater than the nitrogen requirements of crops. Zhang *et al*. estimate that the global average efficiency of nitrogen use in crops is only 42%, and they argue that there is a potential to improve this efficiency globally to 67%, which could significantly reduce the global demand of fertilisers by 2050[4]. The maximum mitigation potential of this intervention is explored in the demand reduction scenario in Fig. 2a.

Fig. 1 shows that in 2019 there were 455.1 Mt CO_2e of direct N_2O emissions, and there were 49.7 and 122.0 Mt CO_2e of indirect N_2O emissions by ammonia volatilization and nitrate leaching, respectively. In total, direct and indirect N_2O emissions in the cropland account for 48% of the total emissions of synthetic nitrogen fertilisers (Fig. 1). These are generated by bacteria, and they could be reduced by the use of nitrification inhibitors. These are chemicals that can be deployed along fertilisers to prevent bacteria from performing nitrification and denitrification reactions. Urease inhibitors can also be deployed to urea to prevent its decomposition into ammonia and subsequently to N_2O[41]. It was reported that the use of nitrification inhibitors also decreases the level of acidification of the soil[42]. For this reason, the use of nitrification inhibitors reduces the requirements for limestone to correct acidification, consequently reducing the total CO_2 emissions. The maximum mitigation potential of using nitrification and urease inhibitors is explored in our nitrification inhibitors scenario in Fig. 2a.

Finally, not all types of fertilisers used globally produce the same GHG emissions per unit of N. Fig. 2b shows this breakdown and reveals that urea, urea ammonium nitrate (UAN) and ABC have some of the worse emissions performances, since their decomposition in soil releases CO_2 in addition to N_2O. However, it is possible to replace these types of fertilisers by some of the best performing, such as ammonium nitrate (AN). The maximum mitigation potential of this intervention is explored in the fertiliser substitution scenario in Fig. 2.

Fig. 2a shows the maximum mitigation potentials of implementing each strategy described above in isolation by 2050. Changing the source of hydrogen for ammonia production from steam methane reforming to water electrolysis powered with renewables (scenario 'water electrolysis') results in a substantial reduction in production emissions. This alone can reduce 75% of production emissions by 2050, but only 27% of total emissions, owing to the much larger weight of use phase emissions. Electrifying the production process (scenario 'electric heating') can also reduce 21% of total emissions by avoiding fuel combustion but retaining process emissions. Deploying CCS to steam methane reforming and coal gasification (scenario 'CCS') can also reduce emissions by 25% by 2050.

Fig. 2a suggests that fertiliser demand reduction is the single intervention with the greatest mitigation potential, as it avoids the production impacts of fertilisers in the first instance, along with their use phase emissions. By increasing the global efficiency of nitrogen use from current 42% to 67% by 2050, the total nitrogen demand could be reduced by 48% N in 2050. A combination of several approaches is needed to achieve the proposed nitrogen use efficiency. This includes proper irrigation, adopting improved plant breeding of crops which utilise nitrogen fertilisers more efficiently and applying the right fertilisers at the right rate and time in the right place[4].

Many of these interventions at the production and use of fertilisers can be deployed simultaneously thus enhancing the total mitigation potential. The emission factor in each lifecycle stage is assumed to change linearly from 2021 to 2050. Fig. 2c explores the maximum combined mitigation potential, and suggests that total 2050 GHG emissions can be reduced by up to 78% to 357 Mt CO_2e a^{-1} in 2050, with a 95% confidence interval of 300-447 Mt CO_2e a^{-1}, when the deployment of water electrolysis for ammonia production is combined with fertiliser demand reduction and the use of nitrification inhibitors. We call this scenario "combination" in Fig. 2c.

Fig. 2b shows that even after fully applying the interventions in the combination scenario, further emissions reductions can be achieved by replacing urea, UAN and ABC by AN. The maximum mitigation potential of this fertiliser substitution combined with the other interventions described above is also explored in Fig. 2c (258 Mt CO_2e a^{-1} in 2050, 95% confidence interval: 210-360 Mt CO_2e a^{-1}). Although this fertiliser substitution when deployed in isolation could lead to a 3% increase in emissions, owing to the current high emission factor of AN, this intervention could increase the total emissions reduction potential up to 84% when coupled with the combination scenario. A more detailed breakdown of GHG emissions for a variety of combined interventions is provided in Section 3 of the SI file.

Sensitivity analysis

The quantification of the maximum mitigation potential of the interventions shown in Fig. 2 is subject to uncertainties, owing to incomplete data and assumptions about various current and future performance metrics. Thus, a sensitivity analysis is conducted to reveal the parameters that most influence the effectiveness of the mitigation options.

Fig. 3 shows that the nitrogen use efficiency is the most sensitive parameter influencing the global GHG emissions of synthetic fertilisers. This is obtained by varying input parameters by the ranges indicated in the literature, and it shows that even in the worst scenario, the interventions tested here still significantly reduce the GHG emissions from current levels. A full description of the procedure followed for this sensitivity analysis is described in the methodology.

Discussion

Feeding the global population with less GHG emissions from nitrogen fertilisers would require a decarbonisation of the production of fertilisers by electrification of heating and the deployment of water electrolysis for ammonia production. However, our results (Fig. 1) show that the production of synthetic fertilisers results in 0.48 Gt CO_2e a^{-1}, which accounts for only approximately 1/3 of total GHG emissions from synthetic nitrogen fertilisers (1.31 Gt CO_2e a^{-1}), with the remainder taking place at the use phase (0.83 Gt CO_2e a^{-1}). For this reason, decarbonising fertiliser production would need to be combined with an increase in nitrogen use efficiency in croplands to the potential maximum values, a deployment of nitrification inhibitors, and a shift in the mix of fertilisers used globally. These are all options with high technology readiness levels, and our results shown that if these interventions are deployed, up to 84% of global GHG emissions of synthetic nitrogen fertilisers can be reduced by 2050.

Although substantial attention has been given to the decarbonisation of the petrochemical industry, achieving this would only reduce approximately one third of current fertiliser emissions. This highlights the priority of a focus on the mitigation of use phase emissions of fertilisers.

The results show that manure is currently not an appropriate substitute for synthetic fertilisers, even without implementing any mitigation interventions. Manure currently emits 1.9 times more GHGs than an average synthetic fertiliser per unit of N, mostly due to additional emissions generated in manure storage and mobilisation. This suggests that unless there are substantial changes in the manure management process that can substantially reduce emissions, the use of manure in croplands as an alternative to synthetic fertilisers results in more GHG emissions. Additionally, it is easier to implement effective mitigation options on the production of synthetic fertilisers, since these are produced in controlled industrial settings.

Fertiliser demand forecasts are based on projections of population growth, resulting crop demand and land use changes. These are modelled by FAO[36,39] and considered in our BAU scenario. These aspects are also modelled by the Integrated Model to Assess the Global Environment (IMAGE) model[43], which in used in our demand reduction scenario. Any diversions from these projections of population growth will inevitably influence the projected demand for food, agricultural land area, nitrogen fertilisers and consequent GHG emissions. Equally, changing diets towards less fertiliser-reliant crops and increasing efficiencies along the food supply chain would enable additional reductions in the demand for fertilisers and GHG emissions[44,45]. Although the influence of changes in these parameters is not explored in this article, exploring this space could identify other opportunities to further reduce the demand for fertilisers.

This study explores the maximum mitigation potential of interventions with universal effects across all world regions. However, the complexity of agricultural production in different regions suggests that other effective mitigation options can be explored for the specific local and regional conditions determined by the type of soil[34], agricultural practices[46], and climate. For example, the deployment and expansion of legume crops to fix nitrogen by the symbiotic relationship with bacteria can be another strategy to further reduce the demand of nitrogen fertilisers and corresponding emissions. Additionally, the impact of no-till farming may also reduce the direct N_2O emission in particular regions[46].

This study has quantified the maximum potential and uncertainty of various mitigation options. However, mitigation interventions on the production or use of fertilisers may not be equally easily deployable everywhere. The vintage of existing production infrastructure may determine the timing of capital investment cycles. For this reason, only new facilities would probably be able to deploy water electrolysis and electric heating for ammonia synthesis, while coupling CCS to existing steam methane reforming may be easier to adopt in existing facilities. Additionally, geographical variations on the availability of suitable CCS storage basins or wind power potential may lead to a local adaptation of the portfolio of mitigation options suggested here.

Although we have only quantified the maximum potential of various interventions to mitigate GHG emissions, these actions can also mitigate other categories of environmental impacts. For example, less use of fertilisers and less nitrate leaching can alleviate eutrophication and drinking water contamination. Also, less volatilisation of nitrogen fertilisers reduces NO_x emissions.

Collective actions from all stakeholders are required to bring about the maximum mitigation potentials explored in this work. Policymakers can promote the increase in nitrogen use efficiency and deployment of cost-effective and mature mitigation technologies. These could be achieved for example by taxing food staples with high fertiliser requirements, alleviating taxes for farms with high nitrogen use efficiency, and regulating the production of fertilisers, including the addition of nitrification inhibitors. Farmers can increase nitrogen use efficiency by adopting more precise guidance on fertiliser use that fosters the application of the right type of nitrogen fertilisers at the right time, in right place, and at right rate. Other crop growth conditions should be considered, such as irrigation, type of soil, and climate.

Methods

The mass flow of nitrogen fertilisers and GHG emissions in 2019

To create the map of nitrogen fertiliser mass flows (Fig. 1), we reconciled publicly available data from the production and consumption of fertilisers across nine world regions: Africa, Latin America, North America, Oceania, Southern Asia, Middle East, Western and Central Europe, Eastern Europe and Central Asia (EECA), and Eastern Asia, and 11 types of fertilisers. The International Fertiliser Association (IFA)[47] reports the consumption of nitrogen fertilisers for all world regions. This includes data on 11 different fertilisers consumed globally, namely ammonia direct application, ammonium sulphate (AS), ammonium nitrate (AN), calcium ammonium nitrate (CAN), ammonium phosphate (AP), NK compound, NPK compound, urea ammonium nitrate (UAN), other N straight (other N), other NP, and urea. These are defined in Section 1.1 of the SI file, along with a description of the method used to estimate the intermediate products used in the production of some types of fertilisers, namely urea, AN and nitric acid. These intermediate products are important to estimate the GHG emissions associated with each type of fertiliser.

In order to account for the GHG emissions at each stage of the production of each type of fertiliser, we considered the required mass of intermediate products as reported above, but also regional variability in fertiliser production and their emissions. For this reason, we considered the same nine world regions as before. Since the GHG emission factor of nitrogen fertiliser production varies in different regions, we estimated the amounts of fertilisers domestically supplied and imported in each region, based on the production and consumption of nitrogen fertilisers reported by the IFA. This then enabled the estimation of emissions associated with the production of nitrogen fertilisers. This procedure is described in detail in Section 1.1 of the SI. The calculation of GHG emissions in CO_2e is obtained by using the global warming potential of N_2O and CH_4 for a horizon of 100 years. IPCC AR6 WGI reports 273 and 27.0, respectively, as the conversion factors for these gases[14].

GHG emissions from the production of fertilisers at different lifecycle stages in each world region are calculated by multiplying the mass of domestically supplied and imported nitrogen fertilisers with the regional and global average GHG emission factors, respectively. The GHG emission factors of nitrogen fertilisers in different regions are estimated by the carbon footprint calculator (CFC) developed by Fertilizers Europe[23,48], which is updated frequently to systematically reflect the up to date GHG emission factors of nitrogen fertilisers in different regions. The detailed method to estimate the GHG emissions from each lifecycle stage is described in Section 1.2 of the SI.

The GHG emissions from the transportation of nitrogen fertilisers are neglected because they have been shown to only account for less than 1% of the lifecycle emissions of fertilisers in country-level studies[24].

The GHG emissions from nitrogen fertilisers in the use phase have five different sources: direct N_2O emissions, $E_{directN2O}$, indirect N_2O emissions from ammonia volatilization, E_{GASF}, and nitrate leaching, E_{LEACH}, CO_2 from the decomposition of urea and ABC, $E_{decomposition}$, and CO_2 from limestone used to neutralise the acidification effect, $E_{limestone}$. After nitrogen fertilisers are applied in the soil, bacterial convert a fraction of nitrogen to N_2O by the nitrification and denitrification effect, leading to direct N_2O emissions. Direct N_2O emissions are calculated based on fertiliser-specific emission factors summarized by Bouwman *et al.*[49], and shown in equation (1). Other GHG emissions are estimated by the IPCC 2019 refinement to the 2006 IPCC greenhouse gas inventories, using their Tier 1 approach[18], as shown in equations (2)-(5).

Nitrogen in fertilisers partially volatises as ammonia and NO_x, which will deposit in the soil and eventually results in indirect N_2O emissions via ammonia and NO_x volatilisation, E_{GASF}[18,50]. Although the volatised atmospheric nitrogen may be partially transported to and deposit in other regions[51], we attribute the corresponding GHG emissions to the region where the original fertiliser has been deployed. The deposited nitrogen from other sources, such as industry and fossil fuel combustion, are excluded from E_{GASF}. Nitrogen losses by leaching to underground water and runoff to surface water are mainly in the form of mobile nitrate (NO_3^-). This mobile nitrate is partially converted to N_2O, thus leading to indirect N_2O emissions from nitrate leaching, E_{LEACH}, which is estimated using equation (3).

$$E_{directN2O}=F_N \times EF_1 \times 44/28 \times 273 \tag{1}$$

$$E_{GASF}=F_N \times Frac_{GASF} \times EF_4 \times 44/28 \times 273 \tag{2}$$

$$E_{LEACH}=F_N \times Frac_{LEACH} \times EF_5 \times 44/28 \times 273 \tag{3}$$

$$E_{decomposition}=F_N \times EF_{decomposition} \tag{4}$$

$$E_{limestone}=F_N \times LT \times 0.12 \times 44/12 \tag{5}$$

where, F_N is the amount of an applied nitrogen fertilizer, Mt N, 44/28 is to convert the mass of nitrogen to N_2O, 273 is the 100-year global warming potential of N_2O updated by IPCC AR6 WGI, $Frac_{GASF}$ is the fraction of nitrogen fertilizer that volatilizes as ammonia and NO_x, EF_4 is the emission factor for N_2O from atmospheric deposited nitrogen provided by the IPCC[18], $Frac_{LEACH}$ is the fraction of applied nitrogen fertilizer that leaches as nitrate, EF_5 is the emission factor for N_2O from leached nitrate, whose updated value is provided by the IPCC[18]. $EF_{decomposition}$ is the conversion factor of the embedded carbon in urea, UAN and ABC, which are 1.57, 0.79 and 3.14 t CO_2/t N, respectively. LT is the demanded limestone to neutralise the soil for per ton of applied nitrogen[25,52], t/t N, 0.12 is the fraction of carbon from $CaCO_3$, 44/12 is to convert the embedded carbon to CO_2.

The mass of nitrogen contained in manure and corresponding GHG emissions are estimated from the 2019 IPCC refinement, using their Tier 1 approach[38]. The heads of animals in each region are reported by the Food and Agricultural Organization (FAO) of the UN[26]. The details are described in Section 1.4 of the SI.

OriginLab 2022 is used to present the results in this study.

Impact of mitigation options

In order to test the impacts of mitigation options, the business as usual (BAU) scenario is defined as a baseline. This considers the forecast of synthetic nitrogen fertiliser demand in 2030 and 2050 from FAO[36], which is based on the expected population growth, crop demand and land use changes. GHG emissions arising directly from land use changes are excluded from our analysis, as these are not the direct result of the production or use of fertilisers. For this BAU baseline, we consider regional annual demand for fertilisers linearly interpolated from 2019 to 2030 and 2030 to 2050, which are the reported years by FAO. We have used the same emission factors as in 2019 for each lifecycle stage. The fraction of imported nitrogen fertiliser and composition of fertiliser demand in each region are kept constant to the same values as in 2019 for this baseline.

Two groups of mitigation options, in the production and use phase, are quantified to investigate their maximum potentials. The details are discussed in Section 2 of the SI.

For the water electrolysis scenario, the consumption of wind power for ammonia synthesis is estimated from the values reported in recent literature[53]. A typical carbon footprint of 11 t CO_2e/GWh for wind power[54] is considered and the energy requirements to convert ammonia to other nitrogen fertilisers are based on the value reported by Fertiliser Europe's CFC.

For the electric heating scenario, wind power is assumed to provide heat for the production process thus completely replacing fuel combustion. In a convectional natural gas-based ammonia synthesis plant, air is premixed in a reactor to provide nitrogen and oxygen for internal combustion. In an electric heating plant, we consider that nitrogen is provided by cryogenic distillation driven by wind power.

For the CCS scenario, the typical energy demands to capture CO_2 from flue gas are extracted from a typical solvent-based CCS facility using monoethanolamine[30]. The pure CO_2 stream from existing ammonia plants is directly compressed to be stored or used for enhanced oil recovery, unless it is used as a feedstock for urea or ABC production. The electricity required to compress CO_2 to 11 MPa by a 4-stage compressor for transport is estimated by considering an isentropic compression process and the energy use efficiency[55].

For the demand reduction scenario, the crop demand forecast is a prerequisite to estimate the demand of nitrogen fertilisers. However, FAO does not report the projections of crop demand and land use changes along with its forecast of nitrogen fertilisers[36]. Thus, we have estimated the volumes of nitrogen in crops for 2030 and 2050 based on the Integrated Model to Assess the Global Environment (IMAGE) version 2.2 developed by the Netherlands

Environmental Agency[43] and the contents of nitrogen in crops[56]. This model estimates crop demand increases across various world regions due to population growth. Given the amount of nitrogen contained in crops, the total fertiliser demand in each region in 2030 and 2050 is then estimated by the nitrogen use efficiency proposed by Zhang *et al*.[4]. This is defined as the ratio between the amount of nitrogen contained in harvested crops and nitrogen inputs. Section 2.5 of the SI provides a detailed explanation of how we considered nitrogen requirements of crops. The contributions of manure in 2030 and 2050 are estimated from the heads of animal forecasted by the FAO[26]. The contributions of biological fixation and atmospheric deposition are assumed to be constant and equal to the values for 2018 estimated by the FAO, since these were relatively stable in recent years[57].

For the nitrification inhibitors scenario, we consider the full deployment of nitrification and urease inhibitors for urea by 2050. The maximum mitigation potential in direct N_2O emission[41], and indirect N_2O emissions from nitrate leaching and ammonia volatilization, as well as the reduction in demand for limestone to neutralise soil acidification[42] are all quantified in the literature. Nitrification inhibitors[34] and deep placement[17] are adopted for other nitrogen fertilisers, whose effects are quantified by the literature. The details are shown in Section 2.6 of the SI.

Uncertainty analysis

We have conducted an uncertainty analysis based on the uncertainties of raw data. We used a Monte Carlo approach for the amounts of domestic supplied and imported nitrogen fertilisers, the emission factors of synthetic nitrogen fertilisers in the production, and emission factors in the use phase. Full details are provided in Section 1.6 and Section 2.8 of the SI.

Sensitivity analysis

The sensitivity analysis is conducted to reveal the parameters that most influence the global GHG emissions for the scenario combination and fertiliser substitution (water electrolysis, demand reduction, nitrification inhibitor and fertiliser substitution) in 2050.

The influence of the future potential nitrogen use efficiency is explored, as this parameter greatly influences the nitrogen fertiliser demand and related GHG emissions (Fig. 2). Additionally, we test the sensitivity of changes in the carbon footprint of wind power, since our intervention on fertiliser production involves a shift towards electrification from renewables. We have also tested the sensitivity of the performance of nitrification inhibitors on direct N_2O emissions, since they are the largest emission source before and after this intervention.

For the results shown in Fig. 2, a typical value of 11 t CO_2e/GWh of the carbon footprint of wind power is assumed[54]. However, various sources propose a range of values for the minimum and maximum carbon footprint of wind power, ranging from 0 to 45 t CO_2e/GWh[54]. We have considered a potential global nitrogen use efficiency of 67% by 2050 as proposed by Zhang *et al*.[4]. We tested the global nitrogen use efficiency ranging from 61% to 72% by changing the regional nitrogen use efficiencies by 5%.

To reduce the N_2O emissions, nitrification inhibitors are used to slow down the nitrification effect of bacteria[33]. Akiyama *et al*. report that DMPP is a safe and effective nitrification inhibitor recommended by the European Union[34] , which can reduce the direct N_2O emission from nitrogen fertilisers by 50%, with a 95% confidence interval between 42% and 55%[34]. Although nitrification inhibitors are proved to be safe in studies[32,58], their use is still not widespread and so further verification should ensure the absence of other yet unknown impacts of their application.

Data availability

The data supporting the findings of the study are available within the paper and its Supplementary Information.

The following databases were used to compute the results shown in Fig. 1 and Fig. 2:

The regional consumptions of nitrogen fertilisers are available from: https://www.ifastat.org/databases/plant-nutrition.

The regional productions of nitrogen fertilisers are available from: https://www.ifastat.org/supply. The shares of imported and domestically supplied nitrogen fertilisers for each region are estimated by a method described in the SI

The forecasted nitrogen fertiliser demands in 2030 and 2050 are available in FAO website: https://www.fao.org/faostat/en/#data/GY.

The emission factors of nitrogen fertilisers in production are obtained from the carbon footprint calculator (CFC) by Fertilisers Europe. This can be accessed from: http://www.calcfert.com upon free registration. The CFC adopts the emission factor of fossil fuel supply reported by Gabi database: https://sphera.com/life-cycle-assessment-lca-database.

The emission factors of nitrogen fertilisers in the cropland are reported by the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The direct N2O emission factors are reported by Bouwman, et al. Global Biogeochem. Cycles 16, 28–1 (2002).

Code availability

The code used for the analysis is generated by Matlab 2022a and is available from https://doi.org/10.17863/CAM.86735 upon request.

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Author contributions statement

Y.G.: data curation, investigation, methodology, writing.

A.C.S.: supervision, conceptualisation, writing.

Competing interests statement

The authors declare no competing interests.

Figure captions

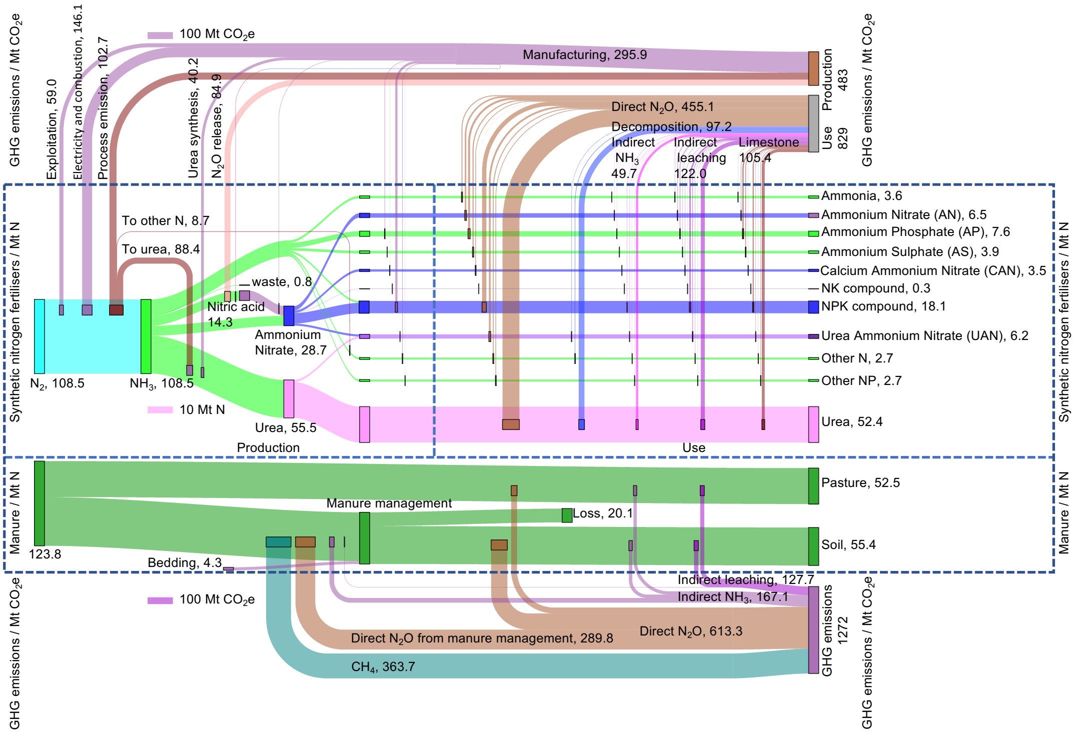

Fig. 1 Sankey diagram of the global mass flow of synthesized nitrogen fertilisers and manure and corresponding GHG emissions in each lifecycle stage in 2019. The horizontal flows represent the mass flows of nitrogen, and the vertical flows show the points of generation of GHG along the supply chain. In both cases, the thickness of the line is proportional to the mass of nitrogen and GHG emissions, respectively. The mass of nitrogen fertilisers flows from left to right, along its supply chain. All values behind this diagram are presented in Section 3 of the SI

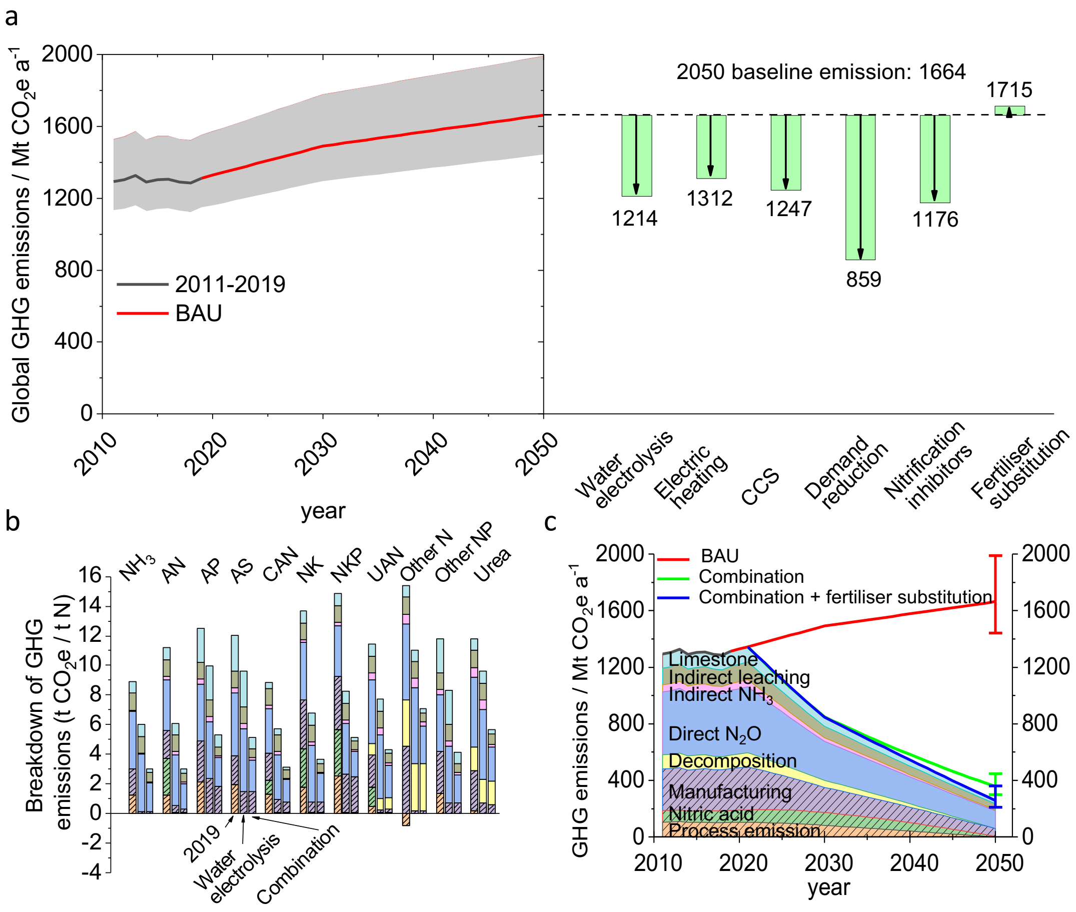

Fig. 2 Mitigation potentials of different strategies. a) Historical and future global GHG emissions from synthesised nitrogen fertilisers. The central lines represent our best estimation (mean value) of the historical and forecasted GHG emissions in the BAU scenario, and the grey area represents the 95% confidence interval estimated by the Monte Carlo approach with 5000 simulations. The columns show the maximum mitigation potential of individual interventions in 2050 if applied in isolation. b) Breakdown of GHG emissions from various nitrogen fertilisers in different lifecycle stages in 2019, 2050 scenario water electrolysis and 2050 scenario combination (water electrolysis, demand reduction, and nitrification inhibitor). The colours represent the same stages of the lifecycle as in Fig. 2c. c) Global GHG emissions for different lifecycle stages for the combination of all mitigation options: use of water electrolysis for ammonia production, deployment of nitrification inhibitors, and the reduction of demand of fertilisers by increasing the nitrogen efficiency (green line), and additionally the replacement of urea, UAN and ABC by AN (blue line). The lines represent our best estimation (mean value) of the GHG emissions in different scenarios, and the error bars

represent the 95% confidence interval of the GHG emissions estimated by the Monte Carlo approach with 5000 simulations.

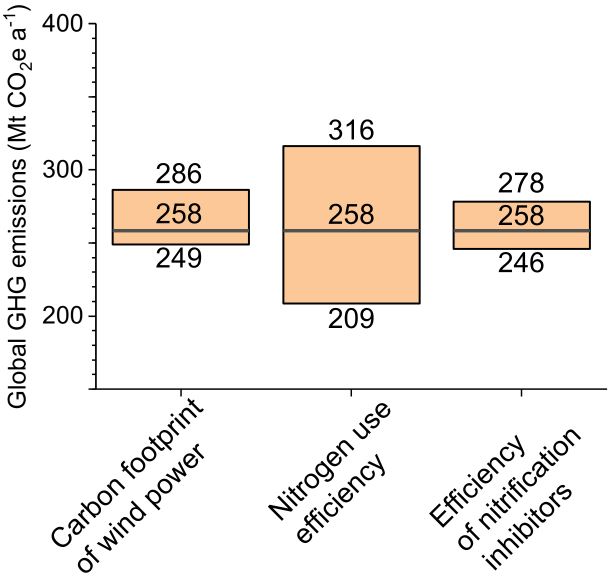

Fig. 3 Impact of the factors on global GHG emissions from nitrogen fertilisers. The central solid lines show our best estimation (mean value) of the projected GHG emissions from fertilisers in 2050 under scenario combination + fertiliser substitution (water electrolysis, demand reduction, nitrification inhibitor and fertiliser substitution). The upper and lower bounds of the boxes indicate the range of GHG emissions when the tested parameters change. The first column shows the global GHG emissions with embedded GHG in wind power ranging from 0 t CO_2e/GWh to 45 t CO_2e/GWh. The second column indicates the effect of global nitrogen use efficiency ranging from 61% to 72% on GHG emissions. The third column shows the impact of nitrification inhibitors on direct N_2O emission reduction from 42% to 55%.

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