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Global agriculture and nitrous oxide emissions

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Nitrous oxide (N_2O) is an important anthropogenic greenhouse gas and agriculture represents its largest source. It is at the heart of debates over the efficacy of biofuels, the climate-forcing impact of population growth, and the extent to which mitigation of non-CO_2 emissions can help avoid dangerous climate change. Here we examine some of the major debates surrounding estimation of agricultural N_2O sources, and the challenges of projecting and mitigating emissions in coming decades. We find that current flux estimates — using either top-down or bottom-up methods — are reasonably consistent at the global scale, but that a dearth of direct measurements in some areas makes national and sub-national estimates highly uncertain. We also highlight key uncertainties in projected emissions and demonstrate the potential for dietary choice and supply-chain mitigation.

The potential for climate change mitigation through reducing emissions of non-CO_2 greenhouse gases has received increasing attention in recent years. The importance of these gases in terms of net anthropogenic climate forcing, and the low or negative marginal abatement costs of many non-CO_2 mitigation strategies, mean that any effective global climate change policy in the twenty-first century must consider them[1]. Nitrous oxide (N_2O) is one of the most important of these non-CO_2 greenhouse gases and agriculture represents its largest anthropogenic source, but the estimation, projection and mitigation of these emissions each poses considerable challenges[2].

Here we synthesize the latest debates over the estimation of agricultural N_2O emissions. We find that so-called top-down and bottom-up estimation methods are reasonably consistent at the global scale, but that an increased number of field measurements of direct and indirect N_2O fluxes is required to improve the reliability of sub-national-scale emission estimates.

For the projection of agricultural N_2O emissions in the next few decades we highlight the challenge of incorporating robust simulations of changing human population, diet and bioenergy demand. We stress the need for improved understanding of interactions between climatic change, changing nitrogen status of ecosystems and agricultural N_2O fluxes.

Finally, we examine the challenge of reducing agricultural N_2O emissions and estimate the potential impacts of dietary change and reducing food wastage. We find that dietary change may serve as a powerful determinant of agricultural N_2O emissions — a simplistic scenario of reducing per capita poultry-meat consumption in the developed world between 2012 and 2020 results in a relative cut in global N_2O emissions associated with this single food source of >100 Gg N_2O-N yr^{-1}.

We also find that avoidance of food loss and wastage may yield substantial reductions in agricultural N_2O emissions. Consumer-phase food wastage of just five food types in the UK, for example, constitutes >2 Gg N_2O-N yr^{-1} of 'avoidable' N_2O emissions. At a global scale, loss and wastage of these same five foodstuffs is associated with production-phase N_2O emissions in excess of 200 Gg N_2O-N yr^{-1} (~3% of the global agricultural N_2O source).

Agriculture and nitrous oxide emissions

Of the approximately 16 Tg N_2O-N yr^{-1} emitted globally in the 1990s, between 40 and 50% was a result of human activities, with much of the growth in N_2O concentrations since the pre-industrial era being attributed to the expansion in agricultural land area and increase in fertilizer use[3]. Currently, the main sources of anthropogenic N_2O emissions are agriculture, industry, biomass burning and indirect emissions from reactive nitrogen[4] (Nr) leaching, runoff and atmospheric deposition[5]. Of these, emissions from agricultural soils dominate[5], widespread use of nitrogenous fertilizers and increasing manure inputs combine to drive emissions growth. With an increasing human population, and the consequent need for more food production, both agricultural land area and N_2O emissions are likely to continue to rise in coming decades[1,7–10] (Fig. 1).

Alongside industrialization and rising emissions of NO_x from fossil fuel burning, the intensification of agriculture and associated NH_3 emissions has led to a three- to five-fold increase in Nr emissions over the past century[11]. This growth in anthropogenic Nr emission and deposition, together with deliberate enhancement of biological nitrogen fixation and the manufacture of Nr for fertilizers and industrial uses, has approximately doubled the global Nr supply relative to the pre-industrial average[3]. As such, agriculture has caused a huge perturbation to the global nitrogen cycle since the industrial revolution, and has significantly increased net N_2O emissions.

The estimation challenge

Direct measurements of agricultural N_2O emissions have been made for many decades. The myriad methods employed and their associated challenges have themselves generated long-running debates[12–15], but these are beyond the scope of this Review. Instead our focus here is on the challenge of estimating agricultural N_2O

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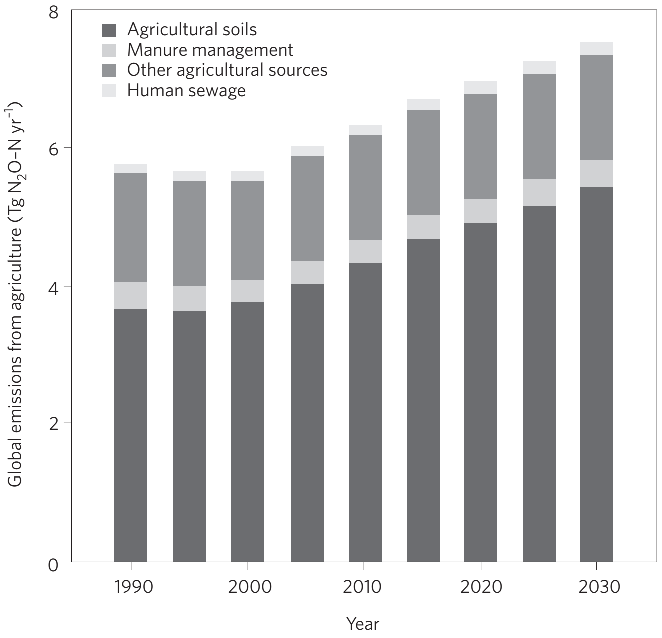

Figure 1 | Global N_2O emissions from agriculture between 1990 and 2030[10]. Emissions from histosols, sewage sludge application, asymbiotic fixation of soil nitrogen, and mineralization of soil organic matter are not included in these estimates. 'Other agricultural sources' here includes field burning of agricultural residues, prescribed burning of savannas and open burning from forest clearing. See Supplementary Information for further details.

emissions for locations and land uses where direct measurements do not exist, or where temporal and spatial scales exceed the coverage of direct measurements.

By more accurately quantifying the relationship between perturbations in Nr inputs and the associated increases in N_2O emissions, we may be able to improve estimates of current and future agricultural N_2O emissions around the world. However, deriving a so-called N_2O 'emission factor' (Box 1) that is representative of this relationship across the very wide range of management systems, climates and land uses that help comprise the global agricultural N_2O source is extremely challenging. Recent years have seen an intensification in the debate over how such N_2O emission factors are derived and applied[9,16,17].

Crutzen *et al.*[16] used a top-down approach to estimate the fraction of newly created Nr that would have to be emitted as N_2O to balance the global N_2O budget in 1860 and in the 1990s. For the pre-industrial period, they estimated an N_2O emission factor of 4.4–5.1% for all newly created Nr (mostly natural, with a small anthropogenic component). For the 1990s a similar N_2O emission factor of 3.8–5.1% seemed to explain the annual increase in atmospheric N_2O concentrations.

Using a combination of bottom-up and top-down methods, Davidson[9] then reported that an emission factor of ~4% of new Nr underestimated atmospheric accumulation of N_2O emissions in the first half of the twentieth century — a period when N_2O concentrations were increasing faster than production of new Nr. This increase in the atmospheric N_2O burden occurred concurrently with increased global manure production, and it was argued that much of the Nr that supported crop and livestock expansion before the Second World War may have been 'mined' from unfertilized, newly tilled soils. The 'mining' of soil nitrogen in this context refers to the depletion of soil organic nitrogen stocks accumulated in the decades or centuries before land conversion to agriculture, and then mobilized as a result of ploughing and overgrazing[18].

Box 1 | Greenhouse-gas emission factors.

Greenhouse-gas emission factors are widely used to estimate emissions arising from a defined unit of a specific activity. Such estimates are used both for international reporting to the United Nations Framework Convention on Climate Change (UNFCCC) and for myriad national and sub-national reporting purposes (for example, European Union Emissions Trading Scheme; EU ETS). As with the other 'Kyoto protocol GHGs', the Intergovernmental Panel on Climate Change (IPCC) provides a methodology for national and sub-national estimation of N_2O emissions, based on the sector from which the emissions arise. Emissions are estimated using Tier 1, 2 or 3 methodologies, where Tier 1 relies on a universal emission factor combined with activity data, Tier 2 utilizes a country-specific emission factor, and Tier 3 involves direct measurement or modelling approaches[22].

For estimation of N_2O emissions from the agricultural sector, Tier 3 estimates are rarely available and default N_2O emission factors are often employed. For example, the Tier 1 IPCC default factor for direct N_2O emissions arising from mineral nitrogen fertilizer application to managed soils is 1% (ref. 22) (that is, 10 kg N_2O-N is emitted for every tonne of nitrogen fertilizer applied). To this would then be added an estimate of the indirect N_2O emissions from nitrogen leaching and runoff, and from atmospheric nitrogen deposition.

These direct and indirect emission estimates do not cover subsequent recycling of the added nitrogen and resulting N_2O emissions, instead these are covered by additional IPCC emission factors such as those for crop residues, manure and sewage nitrogen[22]. As such, direct comparisons of 'bottom-up' emission factors to those derived using global 'top-down' methods[16] cannot be made due to the differing ways in which the sources of nitrogen inputs are considered[17].

Davidson[9] showed that, when manure production and synthetic fertilizer-nitrogen were partitioned as separate sources of N_2O emissions (with emission factors of 2% and 2.5% respectively), the observed increase in N_2O concentrations for the entire record of atmospheric measurements from 1860 to 2005 could be explained. This finding highlights the need to consider the 'cascade' effect[19] of Nr, with manure production being one of several phases of recycling of Nr. Recent calculations[20] show that if the Crutzen *et al.*[16] concept of newly fixed Nr is broadened to include NO_x deposition and the Nr mined from hitherto virgin land, then the application of a simple 4% emission factor does give a close fit to the observed trend in atmospheric concentration. Thus the Crutzen *et al.*[16] explanation of anthropogenic emissions remains plausible, based on the primary N_2O emissions from fertilizer, biological nitrogen fixation, mining of soil organic N and NO_x sources being followed by emissions of recycled Nr in manure production and management.

Top-down and bottom-up estimation. The Crutzen *et al.*[16] estimate raised the question of whether the bottom-up-derived N_2O emission factors used by the IPCC (for example Box 1) and others may, in aggregate, substantially underestimate emissions. However, there is little evidence for any such systematic underestimation at the global scale, with estimates made using the IPCC method[17] being within the range generated using the Crutzen *et al.* method (Table 1). Del Grosso *et al.*[17] noted that, as scale increases, agreement between bottom-up and top-down estimates also increases. Indeed, this convergence of estimates derived from different methods itself increases confidence in the absolute values[17].

At regional and sub-regional scales however, neither approach can reliably estimate emissions in all circumstances. Freibauer[21]

Table 1 | Recent estimates of agricultural N_2O emissions (Tg N yr^{-1}) using different methodologies.

Source	Del Grosso *et al.* (bottom-up)[17,22]	Del Grosso *et al.* (top-down)[16,17]	Syakila & Kroeze[6]	Syakila & Kroeze[6]
Direct	3.8	} 4.2–7.0	1.8	2.2
Animal production	0.4		2.3	2.3
Indirect	1.6		1.3	2.6
Total	**5.8**[*]	**4.2–7.0**[†]	**5.3**[‡]	**7.1**[§]

[*] Bottom-up, used IPCC 2006 methodology[22]. [†] Top-down, used Crutzen *et al.*[16]. N_2O emission factor of 3–5% for N inputs from symbiotic N fixation and synthetic fertiliser production. [‡] Bottom-up, used IPCC 2006 methodology[22]. [§] Bottom-up, used revised IPCC 1996 methodology[5].

has shown good agreement between measured N_2O emissions in Europe and those derived from the bottom-up IPCC methodology — but one might expect this given that the IPCC emission factors are themselves informed strongly by European measurements.

The top-down approach is currently limited by uncertainties in the temporal and spatial attribution of observed changes in atmospheric N_2O concentrations, whereas bottom-up approaches employing default emission factors may fail to properly represent the heterogeneity among local conditions[17,21]. The use of national and sub-national emission factors, or process-based models attuned to local climate, soil characteristics and land-management practices can help to reduce such uncertainty[17]. So too can on-going revisions to default emission factors, based on new evidence and a wider geographical spread[22]. An exemplar case of such revision is that of the indirect component of agricultural N_2O emissions (Syakila and Kroeze[6]; Table 1). There, a recent update of the default emission factor for N_2O production in aquatic systems, due to agricultural nitrogen leaching and runoff, was made possible by an expansion in the number of field measurements[6,22–24]. The additional measurements led to a reduction in this indirect N_2O emission factor (called EF_5-g) from 0.025 to 0.0075 kg N_2O-N kg^{-1} N input, and the 50% overall reduction in estimated indirect emissions seen in Table 1 (from 2.6 to 1.3 Tg N_2O-N yr^{-1})[6].

A central aim of future research into N_2O emissions from agricultural systems should therefore be to increase the global coverage of direct and indirect N_2O flux measurements to encompass all major agricultural land-use types and climates, land-use changes and management practices. Such data could then provide robust 'Tier 2' emission factors for these systems and increase confidence in national and sub-national estimates. Addressing the current paucity of direct N_2O measurements in much of the developing world is of particular importance. Increased investment in monitoring has the potential to improve the reliability of farm-scale emission estimates, and so gain greater access to mitigation financing through the compliance and voluntary markets[25,26].

The projection challenge

Projected N_2O emissions associated with agriculture are sensitive to drivers such as human population, per capita caloric intake, and consumption of livestock products. Alongside continuing growth in global population[27], per capita food consumption is projected to increase in the next few decades[28], with demand for meat and dairy products being especially strong[28–30] (Fig. 2). These projections represent changes in global average per capita intake, much of the expected increase being driven by greater per capita cereal, meat and dairy consumption in developing-world nations[29]. As a result of the necessary expansion in crop and livestock production to meet this demand, a substantial increase in N_2O emissions from agricultural soils is projected through to 2030[10,31].

Overall, N_2O emissions associated with agriculture (including human sewage) are projected to rise from around 6.4 Tg N_2O-N yr^{-1} in 2010 to 7.6 Tg N_2O-N yr^{-1} by 2030[10] (Fig. 1), with much of this growth resulting from increased nitrogen-fertilizer use in non-OECD Asia, Latin America and Africa. Although these projections provide a useful indicator of future emissions, uncertainties around agricultural demand, interactions with climate change, and the extent of mitigation efforts remain significant.

Agricultural demand and bioenergy. As discussed previously, future changes in human population and diet are a central determinant of global food demand, and so of agricultural N_2O emissions. In addition to the challenge of developing robust scenarios for food-related emissions, projections must also take account of potential increases in demand for bioenergy.

Several recent studies have shown that an outcome of imposing mitigation regimes that value only carbon from energy and industrial sources is that they can create incentives to increase bioenergy production and use[32,33]. Global production of wheat, coarse grains and vegetable oils for biofuels use, for example, is projected to rise from around 160 million tonnes in 2010 to over 200 million tonnes by 2020[29]. Expanded bioenergy programmes can, in turn, increase terrestrial carbon emissions globally by increasing the conversion of forests and unmanaged ecosystems to agricultural use — a perverse result of curbing fossil-fuel-related emissions[34]. Increased production of first-generation energy crops (for liquid transport fuels — bioethanol and biodiesel) may also increase N_2O emissions, as large areas of these crops are fertilized to maximize production. However, many second-generation energy crops do not require large nitrogen-fertilizer additions, and their impact on N_2O emissions is likely to be much lower[35]. A central question therefore, is the degree to which global biofuel crop production will transition to second-generation energy crops, and the extent to which any expansion in production will be confined to existing managed land.

A recent analysis of global biofuels programmes that employ advanced cellulosic (second generation) technologies estimates that, over the twenty-first century, N_2O emissions will be larger than the carbon losses associated with land-use change and land clearing[36]. Cumulative projected N_2O emissions in the analysis by Melillo *et al.*[36] range between 510 and 620 Tg N_2O-N for the period 2000–2100, depending on how much of the new biofuels production is confined to already managed land, and so minimizes new forest clearing. Whereas cumulative N_2O losses continually grow over the twenty-first century, net carbon flux influenced by biofuels production exhibits one of two distinct patterns: a substantial flux to the atmosphere (a land source) if the increase in biofuels production involves extensive forest clearing to establish biofuels crops (deforestation case); or a small flux to the land from the atmosphere (a land sink) as carbon slowly accumulates in the soil fertilized in the biofuels areas (intensification case). A global greenhouse-gas emissions policy that both protects forests and encourages best practices for nitrogen-fertilizer use[37] may therefore dramatically reduce emissions associated with biofuels production.

Feedbacks and interactions. Further increases in anthropogenic Nr inputs to both managed and natural ecosystems are predicted[38]. Agriculture accounts for about 75–85% of projected global NH_3 emissions throughout 2000–2050 and it is likely that regions with soils and ecosystems where Nr loads are already high are more prone

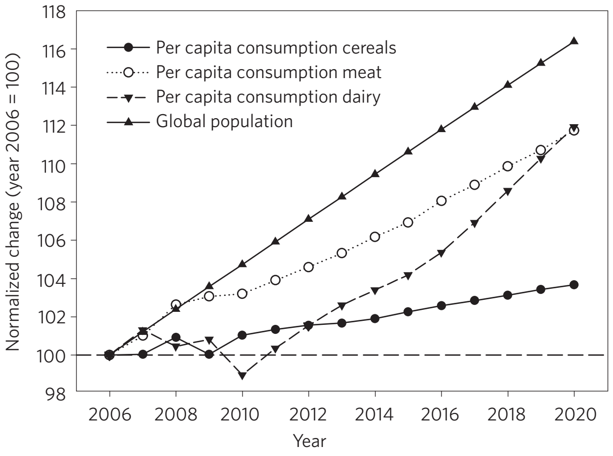

Figure 2 | Normalized change (base year 2006) in projected global population[27] and global average per capita consumption of cereals, meat and dairy products between 2006 and 2020[29].

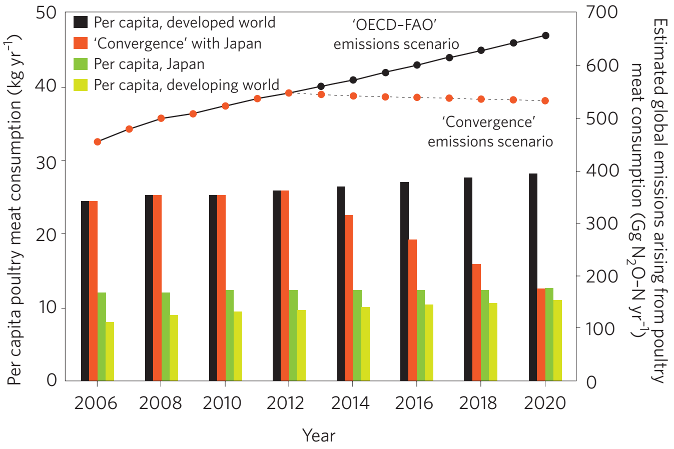

Figure 3 | Average per capita poultry-meat consumption between 2006 and 2020. The developed world (black bars), Japan-only (green bars), the developing world (yellow bars), and a 'convergence' scenario whereby average per capita consumption in the rest of the developed world converges with that in Japan between 2012 and 2020 (red bars). Lines show estimated global N_2O emissions arising from poultry-meat consumption using the OECD-FAO[29] consumption scenario (black circles) and the 'convergence' scenario (red circles). See Supplementary Information for further details.

to Nr deposition-induced N_2O emissions[39,40]. Indeed, significant enhancements (50–60%) in the proportion of new Nr input emitted as N_2O have been reported for riparian forest soils exposed to a decade of NO_3-rich runoff[41]. Insufficient field data exist to confidently include a positive feedback response in regional or global-scale projections of indirect N_2O emissions from agriculture, but it is possible that an expansion in the area of nitrogen-saturated natural ecosystems globally will serve to increase N_2O emissions per unit of Nr deposition in the future. As the microbial processes of nitrification and denitrification are responsible for the bulk of agricultural N_2O emissions[42–44], a greater understanding of the microbiological basis of N_2O fluxes may also help to improve such feedback projections[45].

Likewise, the impacts of future climate change on soil nitrogen cycling and net N_2O emissions from agriculture are potentially significant[46], yet remain difficult to quantify at a global scale. A recent examination of modelled N_2O emissions from Australian pasture-based dairy systems under future climate change scenarios indicated an increase in emissions of up to 40% (ref. 47). Here, warmer soil temperatures coupled with wet, but unsaturated, soils during cooler months resulted in an increased opportunity for N_2O production. Enhanced N_2O emissions from upland agricultural soils under increased atmospheric CO_2 concentrations have also been reported[48]. Conversely, modelling of N_2O emissions from a humid pasture in Ireland under future climate change indicated that a significant increase in above-ground biomass and associated nitrogen demand would serve to avoid significant increases in N_2O emissions[49]. Although direct studies of agricultural N_2O fluxes under simulated future climates do suggest increased emissions in response to warming[50] or increased CO_2[48], examination of the combined effects of warming, summer drought and increased CO_2 indicate that temperature change may be of most importance in temperate, extensively managed grasslands[51]. Overall, it is likely that changes in food demand, land management and nitrogen-use efficiency will be much more important determinants of global N_2O emissions than climate change in the twenty-first century. However, significant indirect effects of climate change on agricultural N_2O fluxes, such as reduced crop productivity[52], altered nitrogen leaching rates[53], and enhanced ammonia volatilization[54,55] require further investigation and quantification.

The mitigation challenge

Agriculture accounted for approximately 60% (~6 Tg N_2O-N) of total global anthropogenic emissions of N_2O in 2005, largely through emissions from agricultural soils after application of nitrogen fertilizer, meaning that the agricultural sector offers the greatest potential for N_2O mitigation[31].

Nitrogen-use efficiency. On average, of every 100 units of nitrogen used in global agriculture, only 17 are consumed by humans as crop, dairy or meat products[56]. Global nitrogen-use efficiency of crops, as measured by recovery efficiency in the first year (that is, fertilized crop nitrogen uptake — unfertilized crop N uptake/N applied), is generally considered to be less than 50% under most on-farm conditions[57–60].

In the agricultural mitigation (Working Group III) chapter of the IPCC's fourth assessment report[31], the global mitigation potential for N_2O reduction in agriculture was quantified using outputs from the DAYCENT model[61]. Projections in demand for food were considered to require an overall increase in fertilizer nitrogen requirements, and large improvements in nitrogen-use efficiency by 2030 (for agronomic rather than climate change mitigation reasons) were assumed in the baseline, leading to a limited potential for mitigation[31,62]. However, given significant over-fertilization in some regions such as China and India[63,64], the mitigation potential may be larger than reported by the IPCC in 2007[65]. Potential mitigation options for N_2O reduction rely on improving nitrogen-use efficiency, which could be increased by up to 50%[66,67] by practices such as changing the source of N, using fertilizers stabilized with urease or nitrification inhibitors or slow- or controlled-release fertilizers, reducing rates of nitrogen application in over-fertilized regions, and optimizing nitrogen fertilizer placement and timing[65,68–70]. In some under-fertilized regions (such as Africa[71,72]) more fertilizer nitrogen may be needed to increase yields. Although the N_2O emissions would be expected to increase, the N_2O emissions per unit of agricultural product may be significantly decreased.

Given the increased demand for fertilizer nitrogen to feed >9 billion people by 2050 (for example, from ~100 Tg to 135 Tg N by 2030[67]) and the potentially very large expansion in biofuel production discussed earlier, N_2O emissions from agriculture are likely to rise in absolute terms. The risk is that large increases in anthropogenic N_2O emissions from the agricultural sector will partly offset efforts to reduce CO_2 emissions from the energy supply sector and

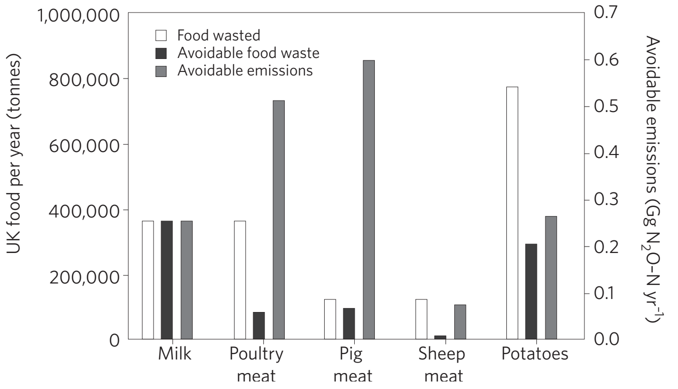

Figure 4 | Estimated mass of consumer-phase food waste (left axis), 'avoidable' food waste, and 'avoidable' production-phase N_2O emissions (right axis) for five food types in the UK in 2009[77,81]. Production-phase N_2O emissions (grey bars) for avoidable food waste were estimated by multiplying the production-phase emission factor[77] for each of the five food types by the mass of each food type wasted in the consumer phase. See Supplementary Information for further details.

others — undermining global efforts to avoid 2 °C of post-industrial warming. A key mitigation challenge, therefore, is to reduce N_2O emissions per unit of fertilizer nitrogen applied, and per unit of agricultural product[73].

Dietary choice. In addition to measures that directly reduce supply side emissions, there exists significant potential for mitigation via the demand side through addressing human dietary choice[70,74]. Just as a shift towards a greater per capita calorific intake and increased proportion of animal products in diets is expected to enhance agricultural N_2O emissions, policies that achieve a reduction in animal product consumption[30,74,75] or successfully address excessive caloric intake[76] can reduce them. For example, Popp *et al.*[30] estimate a 24% reduction in global soil N_2O emissions by 2055 under a 'decreased meat' scenario, where per capita calorific intake increases as a function of GDP, but the share of livestock products in this intake is reduced by 25% every ten years between 2005 and 2055.

Such mitigation potential of dietary change for future agricultural N_2O emissions can be further exemplified by using OECD-FAO projections[29] for per capita meat intake through to 2020 (Fig. 2). For example, by combining average per capita poultry-meat intake in the developed and developing world with projected population change[27], and by then applying an estimate of production-phase N_2O emissions for poultry meat[77], global emissions are seen to increase from 548 Gg N_2O-N yr^{-1} in 2012 to 657 Gg N_2O-N yr^{-1} by 2020 (Fig. 3). Part of this increase is driven by further rises in average per capita poultry-meat consumption in the developed world (from 25.6 kg per capita per yr in 2012 to 28 kg per capita per yr in 2020). However, if per capita intake in the rest of the developed world over this period were instead to converge with the relatively low levels estimated for Japan (the 'convergence' scenario), global poultry-meat-related N_2O emissions would actually decrease to 533 Gg N_2O-N yr^{-1} (Fig. 3). Relative to the estimate derived from OECD-FAO per capita consumption projections, this 'convergence' scenario would constitute a 50% decrease in developed world poultry-meat N_2O emissions and a 19% decrease in global emissions.

Similar potential reductions are seen when per capita pig and sheep meat consumption are examined. Using the methodology outlined above (see Supplementary Information for details), global N_2O emissions in 2020 arising from pig meat consumption fall from 615 Gg N_2O yr^{-1} (using OECD-FAO projections) to 546 Gg N_2O yr^{-1} under the 'convergence' scenario; sheep meat emissions are reduced from 123 to 107 Gg N_2O-N yr^{-1}.

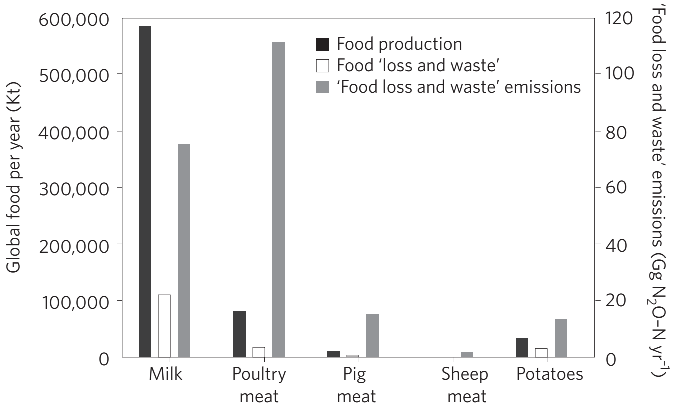

Figure 5 | Mass of global production (left axis) for five food types in 2009[29], estimated 'loss and wastage' along supply chain[80], and estimated N_2O emissions[77] (right axis) associated with the production of 'lost and wasted' food (grey bars). See Supplementary Information for further details.

Clearly, such estimates provide only an indication of how mitigation of agricultural N_2O emissions may be achieved through dietary change. The N_2O emission factor for meat production is likely to vary considerably between locations, and over time. Also, any apparent reduction in emissions observed with the decrease in per capita poultry, pig or sheep meat consumption in developed-world diets must be set against any resultant increases in consumption of other foodstuffs.

An additional challenge in projecting and mitigating food-related N_2O emissions, therefore, is that of obtaining robust estimates of N_2O emission intensities for different foodstuffs in different geographical locations. An emerging area of food-related N_2O emissions that requires just such investigation is that of the aquaculture industry — an industry that has grown at an annual rate of 8.7% since 1970[78], but for which the amount of N_2O produced globally remains poorly quantified[79]. Williams and Crutzen[79] estimate current emissions from this source at around 0.12 Tg N_2O–N yr^{-1}, and suggest that this may rise to more than 0.6 Tg N_2O-N yr^{-1} within 20 years if the aquaculture industry continues to grow at its current rate. For these estimates they employ an N_2O emission factor of 5% for fish farm waste and 2% for human wastewater, while acknowledging the dearth of direct measurements and the urgent need for quantification of N_2O emissions from global carp and shrimp farming in particular.

Food loss and waste. Alongside interventions aimed at reducing average dietary N_2O emissions intensity, reductions in food loss and waste — especially for N_2O-intensive foodstuffs — may also help address agricultural N_2O emissions through the demand side. A simplistic comparison of global average food loss and wastage rates (~30%)[80] with agricultural N_2O emissions (Table 1) would suggest potential N_2O emissions reductions through complete avoidance of food loss and wastage in excess of 1 Tg N_2O-N yr^{-1}. The realistic potential for such mitigation will inevitably vary depending on food type, production and location, but a useful example is that of milk wastage in the UK. Of the 13 million tonnes of raw milk produced for domestic consumption in the UK in 2009[29] some 360 thousand tonnes (~3%) was wasted in the consumer phase[81]. Of this, more than 99% was designated as 'avoidable wastage'[81] and constituted avoidable emissions of 0.25 Gg N_2O-N yr^{-1} (assuming 7.1 kg N_2O-N per 10,000 litres[77]). Almost half of this milk wastage was a result of too much being served, with the rest being discarded as too old[81]. Although milk is a relatively N_2O-intensive product and constitutes a large proportion of avoidable food waste[80], a wider examination of avoidable consumer food wastage in the UK underlines the potential for demand-side mitigation (Fig. 4).

For wastage of the five foodstuffs examined (milk, poultry meat, pig meat, sheep meat and potatoes), emission reductions in the UK totalling more than 2 Gg N_2O-N yr^{-1} seem achievable. As such, interventions aimed at altering consumer behaviour — such as towards smaller purchasing, serving and consumption volumes — have the potential to significantly reduce agricultural N_2O emissions in the UK.

At the global scale, N_2O emissions associated with the production of food that is lost or wasted can be approximated using an average supply-chain loss rate[80] in combination with global production data[29] and the production emission factors used above[77] (Fig. 5). Food 'loss and wastage' is here defined as the mass of a food directed for human consumption that is lost or wasted in the supply chain. Food 'losses' refer to a decrease in the edible food mass at the production, post-harvest and processing phases. Food 'wastage' refers to a decrease in the edible food mass in the retail and consumer phase.

For the five food types examined, loss and wastage-associated emissions total more than 200 Gg N_2O-N yr^{-1} along the supply chain (~3% of global N_2O emissions from agriculture for these five food types alone). Again, the proportion that is realistically avoidable will vary greatly depending on food type, location and stage in the supply chain, but very substantial emissions reductions seem possible by addressing distribution and consumer-phase wastage[80,82].

Conclusion

In this Review we have examined agriculture's current and potential future role in global N_2O emissions. We find that recent estimates of agricultural N_2O emissions using top-down and bottom-up methodologies are in reasonable agreement at the global scale, with consideration of N_2O emissions arising from recycled nitrogen (such as manure nitrogen) being important in the convergence of these estimates. An on-going challenge in estimating national and subnational fluxes is the limited geographical spread of measurements, whereas for projecting future fluxes robust modelling of human population and diet is vital. Direct measurements of N_2O emissions from fast-expanding food-production sectors, such as aquaculture, are also urgently required if global projections of food-related emissions are to be improved.

For mitigation, improving nitrogen-use efficiency in agricultural production remains a key strategy by which increased food demand in the future can be met without a commensurate increase in N_2O emissions. However, we suggest that very significant emissions reductions may also be achieved by better addressing dietary choice and food wastage. Relatively high per capita meat intake and consumer-phase food wastage in the developed world indicates such interventions may be especially effective in some of the richer nations.

Future studies should explore the drivers of national-scale dietary change and food wastage in more depth. Such work may then help identify interventions that would reduce average dietary N_2O emissions intensity and highlight points in the supply chain where the most effective waste reductions can be made.

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Author contributions

D.S.R. conceived the Review, conducted the analyses of diet and food waste impacts, and prepared the manuscript. All authors contributed in the writing and editing of the manuscript.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/natureclimatechange. Reprints and permissions information is available online at http://www.nature.com/reprints. Correspondence should be addressed to D.S.R.