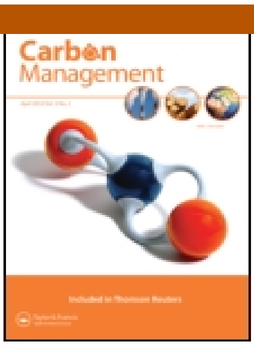

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Importance of non-CO_2 emissions in carbon management

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Importance of non-CO_2 emissions in carbon management

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Background: GHG budgets highlight a need for urgency, yet analyses are often CO_2-focused, with less attention paid to non-CO_2. **Results:** In this paper, scenarios are used to explore non-CO_2 drivers and barriers to their mitigation, drawing out implications for CO_2 management. Results suggest that even optimistic technological and consumption-related developments lead to on-going increases in global N_2O, largely to improve food security within a changing climate. This contrasts with existing analysis, where lower levels of N_2O by 2050 are projected. **Conclusions:** As avoiding '2°C' limits the emissions budget, constraints on reducing non-CO_2 add pressure to energy system decarbonization. Overlooking how a changing climate and rising consumption restricts efforts to curb non-CO_2 will result in policies aiming to avoid 2°C falling short of the mark.

Background and framing

At the Durban 2011 climate negotiations, it was decided 'to adopt a universal legal agreement on climate change as soon as possible, and no later than 2015' [1]. This decision thereby fails to agree measures to curb emissions commensurate with the global ambition of avoiding a 2°C temperature rise above pre-industrial levels. According to the IPCC Working Group III, future global temperatures can be limited to a 2–2.4°C rise above pre-industrial levels, but *only if* global emissions peak by 2015 [2]. Without a legally binding and widely adopted agreement by 2015, the most likely outcome is continued high emissions growth well beyond this, leaving little chance of remaining below the 2°C threshold [3–5]. The apparently conflicting messages emerging from the negotiations – that emissions must commensurate with avoiding 2°C [6], but that agreement will not be reached in time to achieve this– stress the importance of developing emission mitigation strategies that, at the same time, consider climate impacts and hence adaptation. A risk-averse strategy would frame adaptation by the most extreme global emission scenarios and mitigation by the lowest; for example, *mitigate for 2°C, adapt for 4°C or higher* [7]. Arguably, the reverse currently underpins climate policies – mitigation measures are more closely aligned with 4°C of warming [3,8], whilst adaptation research tends to focus on preparing for impacts associated with 2°C, largely because many emission scenarios will reach a 2°C warming around 2050. Addressing climate adaptation and mitigation in unison adds complexity but is essential in the case of the food system, where the climate has direct impacts on agricultural production. In this paper, bottom-up UK scenarios focused on the food system are used to infer global non-CO_2 emission pathways, by exploring different levels of mitigation and climate change impacts in the context of shifting levels and patterns of consumption. Understanding constraints on curbing non-CO_2 provides additional guidance for managing CO_2 budgets constrained to avoid a 2°C temperature rise.

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Key terms

Scenarios: Qualitative and quantitative descriptions of a range of 'what if' futures.

Non-CO_2 emissions: In this paper, taken to be the GHG N_2O and CH_4.

Cumulative emissions: Emissions of long-lived GHG that accumulate in the atmosphere.

Food system emissions: GHG emissions released into the atmosphere that are produced by the full supply chain associated with food, from consumption to production.

Consumption-based emissions: GHG emissions associated with the goods and services consumed by residents from a particular nation.

What sets the food system apart from most other sectors is the relative importance of **non-CO_2 emissions** compared with CO_2, particularly N_2O released from soil, manure management and related to agricultural fertilizers and CH_4 produced by livestock. Although some scenario modelling exercises do consider multi-gas emission pathways with direct relevance for non-CO_2 emission mitigation [9,10], typically more attention within the climate change mitigation literature is given to CO_2 abatement, particularly from the energy system. Studies that do address non-CO_2 mitigation show that there is a high degree of uncertainty over how to significantly curb and quantify these emissions [11–15], particularly N_2O released from soils. These mitigation challenges are further exacerbated when taking into account a rising demand for food in general, projected rises in meat consumption specifically [16] and the impacts of climatic change [17–21]. Consequently, emissions of both N_2O and CH_4 have strong technical, environmental as well as socio-economic drivers including population, rising temperatures, changing food consumption patterns and agricultural methods, which all require attention.

To meet a need for approaches that can deal with complexity addressing adaptation and mitigation in unison [22] and to investigate potential non-CO_2 mitigation challenges faced at a global scale, a suite of UK-focused food system scenarios developed through a participatory approach are drawn upon [23]. The scenarios are grounded quantitatively by an assessment of how climate change and different agricultural technologies and practices modify the emissions intensity of agricultural production. Qualitatively and quantitatively, these include expert stakeholder input and layperson focus group perspectives. Additionally, these build upon and complement similarly detailed policy-relevant analysis focusing on energy system transitions [24–26] as well as other scenarios of the food system [27–29].

Building on the UK food system scenarios, the potential scale and importance of non-CO_2 emissions are addressed globally. A **cumulative emission** framing is applied to draw attention to the influence over coming decades of climate change, a rising population, changing consumption patterns and improvements to the emissions intensity of agricultural production. Whilst many integrated assessment modelling studies offer predominantly top-down interpretations of what levels of non-CO_2 emissions are needed to avoid particular levels of climate change, the process of a 'reality check' is provided here using a bottom-up approach. Furthermore, the emerging impacts of climate change and extent to which non-CO_2 emissions are likely to be affected is an under-researched area with explicit relevance for managing CO_2, the importance of which is highlighted by this type of broad-view analysis.

Finally, the analysis uses a global cumulative emissions framing, given that cumulative emissions of CO_2 equivalent are approximately linearly related to global mean surface temperature [30, p. 20]. Shifting the focus towards non-CO_2 pathways strengthens understanding around the challenge faced in mitigating and managing CO_2. Whilst N_2O emissions have a similar lifetime to CO_2 [31], the lifetime of CH_4 is shorter; nevertheless, using CO_2 equivalent with a time horizon of 100 years is appropriate for exploring implications of non-CO_2 pathways under a constrained budget. Without significant attention paid to non-CO_2 emissions, it is feasible that these could become the largest share of the GHG budget in future, assuming CO_2 mitigation is successful. Building on the bottom-up scenarios that can accommodate the complexity of the 'real-world' system, the objective of this paper is to describe potential future UK and global non-CO_2 emission pathways until 2050, discuss opportunities and barriers to non-CO_2 mitigation and draw out implications for energy system decarbonization.

This paper uses observations and findings from a scenario exercise that can be used to inform global non-CO_2 pathways. These UK scenarios were developed by the authors and published elsewhere [23,32–34]. The 'Data and methods' section describes core elements of the scenarios including methods, baseline data and scenario inputs. The 'Results' section describes the key findings from the scenarios describing non-CO_2 mitigation options and barriers. The 'Discussion' section uses the analysis to develop global non-CO_2 emission pathways and compares them with the wider scenario literature including the representative concentration pathways (RCPs) [101]; the section goes on to draw out the implications for cumulative GHG emissions and for managing and mitigating CO_2. The final section draws conclusion.

Data and methods

Drivers of per capita non-CO_2 emissions are considered through a suite of UK consumption-focused scenarios. As scenarios are designed to support strategic planning in the face of uncertainty [35], these are particularly informative for exploring **food system emissions**, where trade-offs between climate impacts, patterns of consumption and mitigation efforts play out [23]. By using a consumption, rather than territorial-based emissions accounting framework [36], the substantial portion of emissions embedded in international supply chains are included (the UK imported

52% of food consumed by mass in 2010 [37]). The scenarios used here were developed using a backcasting approach [38] that built upon a similar exercise used to develop energy scenarios [39]. In backcasting, a strategic objective is set – in this case to reduce emissions and consider climate impacts commensurate with either low or high climate change, characterized by either a '2°C' or '4°C' warming above pre-industrial levels. Backcasting is most suitable when considering futures that are radically different from the present day in order to break from existing trends and to produce a range of futures whilst meeting a set strategic objective. As such, devising a 'business as usual' comparative scenario, as would normally be the case with 'forecasting' approaches, is not a part of the process. Furthermore, over such long timescales, and with the anticipated level of climate change, it is not possible to conceive a business as usual scenario.

Quantitative modelling was coupled with a process of iterative stakeholder engagement to ground model input assumptions and assess their feasibility, refine the quantification and generate plausible scenario narratives [29]. Stakeholders were consulted from industry, government, NGOs and academia during the scenario development. The main aspects of developing the scenarios – establishing a baseline and scenario construction – are discussed in the following text. Whilst the focus of this paper is non-CO_2 emissions, particularly those related to the food system, the original scenario modelling included economy-wide quantification of all GHG emissions within a cumulative budget framing. More details on the consumption-based modelling approach used are discussed by Wood *et al.* [34,40].

Food system baseline per capita non-CO_2 emissions

Establishing baseline **consumption-based emissions** involves estimating the emissions intensity of goods and services, encompassing emissions at all stages in the supply chain, combined with quantities and types goods and services consumed. These are calculated using the environmentally extended multiregional input output model (EEMRIO) at the core of the 'ASK-REAP' scenario tool [40]. The model uses data from the Global Trade Analysis Project 7 database [41], GHG emissions impacts from Galli *et al.* [42] and UN population statistics [102] to estimate both baseline UK consumption emissions and those associated with the user-defined scenarios. Global warming potentials (GWP) of 310 for N_2O and 21 for CH_4 were embedded within the EEMRIO tool, which are adjusted given more recently published GWP figures within the latest IPCC report of 298 for N_2O and 34 for CH_4, both assuming the inclusion of carbon cycle feedbacks [31]. To simplify the analysis, global supply chains are grouped into four 'regions': UK, rest of Europe, other Annex B nations and non-Annex B nations (referring to the classification of countries used within the Kyoto Protocol). This allows detailed pictures to be developed of the emissions occurring along global supply chains that provide food and other goods and services for consumption in the UK, wherever in the world the products are produced. The baseline emissions are compared with territorial emission estimates given in Table 1. Of the four regions, only the non-Annex B regions have the territorial (production-based) emissions higher than the consumption-based figure, reflecting their lower emissions impacts from consumption and wealthier nations' reliance on imports from less wealthy nations.

A baseline year of 2004 is chosen due to completeness of global data required for the EEMRIO at the time of the scenario development. Whilst the UK's per capita N_2O emissions under the territorial approach are less than the average in other Annex B (including EU) nations, its consumption-based emissions are higher, reflecting higher levels of imported food and textiles. By contrast, for CH_4, the other Annex B region has higher territorial and consumption-based per capita emissions than the UK mainly due to higher CH_4 emissions from landfill waste and meat consumption. A breakdown of the UK's total economy consumption-based inventory for the baseline year is presented in Figure 1. Disaggregation is based on the sector of final consumption, with the 'Food & Drink' sector contributing the greatest proportion of non-CO_2 emissions.

Table 1. 2004 Territorial and consumption-based non-CO_2 per capita emissions using the REAP environmentally extended multiregional input output model.

Emissions per capita in 2004	UK		Rest of Europe (–UK)		Other Annex B		Non-Annex B		All Annex B	
(tCO_2-e/per)	N_2O	CH_4	N_2O	CH_4	N_2O	CH_4	N_2O	CH_4	N_2O	CH_4
Territorial	0.65	1.19	0.81	1.46	0.85	3.05	0.36	1.29	0.83	2.36
Consumption	1.10	2.50	0.96	2.22	0.93	3.51	0.33	1.15	0.95	2.97

Data taken from [40–44] and [102].

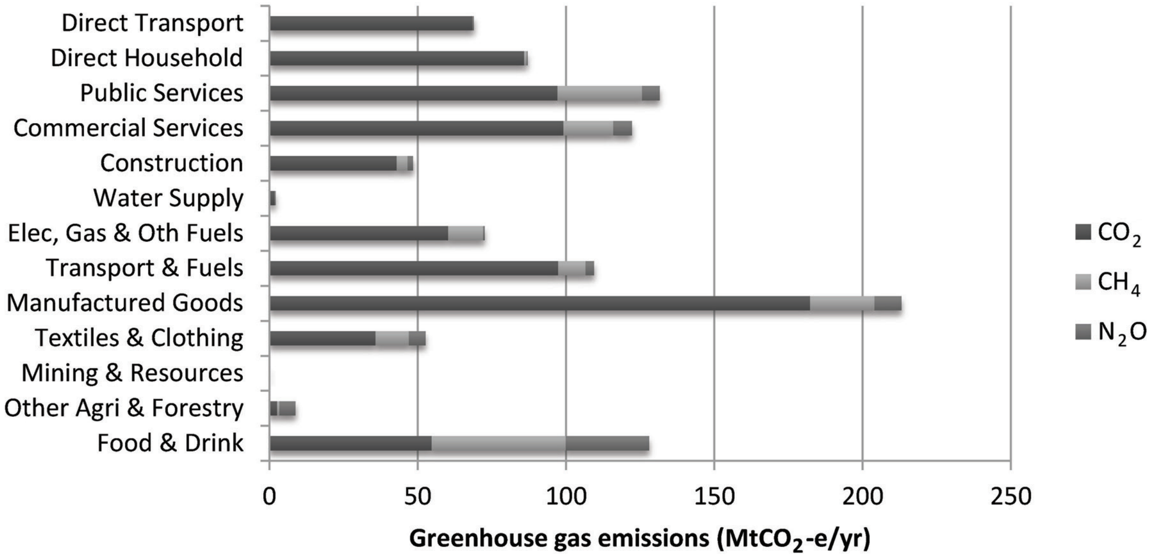

Figure 1. Consumption-based GHG emissions baseline for the UK in 2004 by sector using the EEMRIO model in ASK-REAP, adjusted with global warming potential figures from IPCC AR5. Data taken from [31]

Constructing food system scenarios

To meet the strategic objective of establishing future food system scenarios commensurate with either ‘2°C’ or ‘4°C’ of average global warming, patterns of demand for food and developments within the food system, which influence the emissions intensity of production, are developed through an iterative participatory process. For UK agricultural production, global average temperature increases by 2050 are interpreted for the UK-scale using data from the UK Climate Projections [45] ‘Low’ (SRES B1) for 2°C and ‘High’ (SRES A1FI) for 4°C. It should be noted that while SRES B1 is the lowest temperature SRES scenario, it would still be expected ultimately to exceed a global 2°C temperature rise [46]. In these UK projections, temperatures are expected to increase by around 1°C more in the southern regions than in the north of the country within the 4°C scenario, while the changes are more uniform in the lower 2°C scenario. On average, these projections capture futures with different levels and patterns of climate change, and hence different implications for agricultural production. For production outside the UK, temperature changes and related climate impacts are based on the literature [47].

Qualitative narratives and assumptions, as presented in Table 1 and in the ‘What’s Cooking’ report [22, pp. 38–47], are translated into levels and types of consumption as well as technological developments relevant to the food system by using a model (ASK-REAP) designed specifically for consumption-based scenario construction [40]. The model uses a standard ‘IPAT’ identity [48] where influences on the consumption emissions are population (P), consumption or affluence (A) and GHG intensity of production or technology (T). Together, these drivers form the IPAT identity:

$$I \equiv P \times A \times T$$

where I is the environmental impact, which in this case would be GHG emissions associated with consumption.

As the GTAP database was split into 57 categories, such as wheat, wood products, oil seeds and so on across the entire economy, it was necessary to convert narrative assumptions into quantitative changes in consumption within the model. For example, a 70% reduction in meat consumption would need to be followed through in a number of categories that capture such a change, including ‘meat: cattle; sheep; goats; horse’ or ‘meat products’. Once this change is made, it translates through into a shift in the emissions associated with consumption in those sectors, taking into account population change. To further alter the outcome in terms of GHG emissions, the emissions intensity of production is modified, again in line with scenario assumptions. Changes in the non-CO_2 emissions intensity of agriculture was done by soft-linking to the lifecycle assessment tool ‘SimaPro’. For associated energy-related emissions, for example, if the land-based transport sector improved its carbon intensity by 90% by 2050, then this change will be reflected in any consumption sector (e.g., meat products) that uses land-based transport within its supply chain, using ASK-REAP. More information on how the scenario tools are connected, and sectors aggregated, can be found in Wood *et al.* [40]. Whilst the development of the scenario method is a contribution in its own right, rather than presenting the method in detail here, this paper instead draws upon the insights provided by the scenario exercise with more detail on the method within [23,32–34,40,49].

Specific elements used for assessing scenario-based assumptions were taken from academic literature, qualitative interviews, stakeholder workshop interactions and GHG accounting analysis. For instance, literature was sourced on the implications for agricultural emissions of rising temperatures (both 2°C and 4°C) as well as studies exploring potential climate impacts on yields [50–55] including elevated levels of atmospheric CO_2 concentration and water availability [56]. Technological mitigation options in the agriculture sector were explored using academic literature [57–60], lifecycle emissions accounting using 'SimaPro' for supply chain emissions intensities [32,61] as well as qualitative in-depth interviews and participatory workshops with 35 industry stakeholders including farmers, retailers and manufacturers [23,49]. From the consumption side, studies assessing implications of a growing demand for food on the need for greater yields and fertilizer inputs were used [20,62–64], with scenario elements assessed through a series of consumer focus groups [33]. For the wider energy system, data from existing low carbon energy scenarios [24] were reconstructed within the new scenario tool [23,40].

Results

Five UK food system scenarios were developed and given neutral names intended to remind the UK stakeholders of the nature of each scenario: *bubble & squeak* (B&S) – a meal typically prepared using left-over foods; *mash & banger* (M&B) – hinting at a reverse from the UK's traditional meat-focussed meal (as 2°C scenarios); *pasta & pesto* (P&P) – a quick-to-prepare meal; *chicken tikka masala* (CTM) – known to be UK's favourite dish in contemporary times, reflecting that meals are no different in future; *lab chops* (LC) – a technologically produced meal (as 4°C scenarios). Scenario parameters only with direct impacts on either emissions intensity of production or per capita consumption are quantifiable. Nevertheless, to provide coherent descriptions for engagement, qualitative elements were included (described in Bows *et al.* [23] and summarized in *Supplemental Table 3, which is available from the article's Taylor & Francis Online page at http://dx.doi.org/10.1080/17583004.2014.913859*). In this research, the scenarios are used as heuristics, with the *process* of scenario development, including literature review, stakeholder engagement and modelling, being more important than the scenarios themselves. In this section, insights from this development process are presented in order to offer a bottom-up understanding of how food system emissions could change in future and what barriers may be faced in curbing these emissions.

Options and barriers to mitigating food system non-CO_2 emissions

Changes to food system non-CO_2 emissions are dominated by alterations to agricultural production methods, climate change as well as levels and types of consumption.

Agricultural production

Agriculture is the dominant source of all N_2O emissions, particularly soil and manure management and nitrogen fertilizer production and use, with energy, industrial processes and sewage treatment making up the rest [65]. Within the UK's consumption-based emissions inventory, the Food & Drink sector contributes the highest proportion of N_2O. Stakeholders identified a wide range of mitigation methods for managing food system N_2O production that largely stem from agricultural production including precision nitrogen application, nitrification inhibitors and optimized manure management [66–68]. The measures subsequently implemented within each scenario correspond to the particular scenario narrative and level of assumed mitigation as developed through analysis and stakeholder engagement.

Unlike N_2O, the production of CH_4 has other significant contributing sectors in addition to agriculture, although globally agriculture makes up 52% of the CH_4 emissions, with the rest produced by energy (27%) and waste (21%) [65]. Agricultural mitigation options discussed by the stakeholders included anaerobic digestion, animal diet, fertility (impacting on annual productivity) and the use of enclosed environments to capture and process emissions. For both N_2O and CH_4, socio-economic and environmental circumstances dictate the extent to which changed agricultural technologies and practices can deliver cuts in emissions at a systems level. Stakeholders suggested that important factors influencing uptake of mitigation options affecting the UK revolve around cost, dominant practices, the aging farming community and attitudes of 'young farmers', existing infrastructure, cultural norms, changing climate as well as a feedback linked to levels and patterns of consumption.

Climate change impacts and adaptation

Soil profile, type and structure, temperature, organic soil content and soil moisture shape the potential to reduce N_2O emissions [69]. Temperature and precipitation affect plant productivity, length of growing season, weeds and pests, changing the level of fertilizer needed for a particular yield [59,60,71–74]. Climate change impacts are difficult to predict, and although rising CO_2 concentrations and temperatures can provide better growing environments, fertilizer input needs to rise to benefit from greater potential yields [61]. For example, in higher latitudes like the UK, yield improvements for wheat of

8–25% by 2050 are projected under the B1 emission scenario [47], with average yields increasing from ~8 to ~10 tonnes per ha, requiring around 20–30 kg nitrogen per tonne of wheat grain to access such yields [57]. This would increase the total N_2O emission from UK's wheat production by about 26% [32,61]. Moreover, increases in extreme weather events such as drought, heavy rain, hail and flood can severely damage crops, potentially obliterating crops and wasting fertilizer. Whilst 'shock' events such as those linked to extreme weather are not possible to model robustly with the scenario tool, the stakeholders considered these to be one of the most important future threats to farming. Nevertheless, the implication is that efforts to curb emissions would be negated by such events, given adaptation strategies can include additional efforts, involving fertilizer, energy and hence N_2O and CO_2 emissions, to salvage remaining crops. This may also in turn lead to consumers purchasing food from non-UK-based sources.

Different climate impacts call for different responses, and adaptation strategies to moderate and extreme climate change vary. Modest shifts include varying agricultural inputs, low-till farming, energy-intensive protective measures including heated greenhouses, crop/variety switching, diversifying production and adjusting timing around agricultural activities. More substantive shifts include farming livestock within protective growing environments or wholesale shifts away from conventional production, including intercropping to build resilience. Some adaptation strategies, notably shifting livestock indoors, could, prior to electricity grid decarbonization, increase CO_2 whilst reducing non-CO_2. Similarly, strategies to cut emissions may be negated by changing growing conditions. On the other hand, planning for worst-case scenario effects of climate change through protective adaptation has a potential co-benefit of providing necessary infrastructure to more readily capture and reprocess non-CO_2 emissions.

Consumption

The highest proportion of non-CO_2 emissions in the UK consumption-based emissions inventory are associated with the Food & Drink sector, largely from N_2O emissions associated with direct soil emissions, production and use of nitrogen fertilizers, manure management and CH_4 from livestock (Figure 1). Rising affluence and population have in the past led to increases in the demand for food and the proportion of food wasted, both driving up the emissions of non-CO_2. Typically, UK citizens consume around 3400 kcal per person per day compared with a global average of 2700 kcal. Nevertheless, the FAO has projected that this figure will rise to around 3500 by 2050 [16]. Furthermore, changes to consumption patterns, particularly the increase in meat within the UK diet, which rose from 72 kg per capita per year in 1970 to around 84 kg per capita per year by 2005, elevates the emissions intensity of the food system [16], with the FAO projecting a further increase to 91 kg per capita per year by 2050 [75].

Within the UK consumption-based scenarios, the most significant dietary change considered was a 70% per capita cut in meat consumption, with the deficit replaced with rises in other food types. However, even with changes to per capita meat consumption, absolute emissions levels are driven by population growth (consistent across the scenarios) as well as growth in per capita consumption levels. Population growth *per se* strongly constrains N_2O mitigation, as crops for consumption and for feed for livestock continue to require manure or mineral fertilizer. Barriers to changing patterns of consumption are confirmed through consumer focus group analysis: moderate changes in meat consumption (20% per capita) were considered in line with financial pressures to reduce expenditure given the context of the 2009–2012 recession, whereas a 70% reduction was perceived too substantial a change for many [33].

Influence of imports

Consumption-based emissions include emissions associated with imports. While according to stakeholders, it is feasible to envisage UK agricultural production at the cutting edge of technology and practice in 2050, emission cuts will be negated to an extent if nations where food is exported from, which at present includes nations without emission targets, cannot make similar advances. Moreover, many of these nations are expected to be more severely affected by climate impacts than the UK, potentially resulting in the release of additional emissions stemming from efforts to maintain yields. Consequently, imports from areas with higher emission intensities of production are undesirable from a mitigation perspective. Within the scenarios, the emissions intensity of imports is always assumed to reduce to some extent, depending on the category that the imported product is within and region of import. Annex B nations have attained improvements on a par with those in the UK in the most stringent 2°C scenarios with more moderate improvements to the intensities of goods imported from non-Annex B nations [23].

■ System-level analysis

The UK-focused scenarios were designed to deliver emission cuts in line with 2°C or 4°C whilst considering the influence of a changing climate. The iterative participatory scenario process co-created knowledge by developing plausible narratives focusing on agricultural methods, climate change impacts as well as patterns and levels of food consumption. While a prerequisite for economy-wide decarbonisation relies heavily on managing carbon produced by the energy system, levels of non-CO_2 emissions from the food system were in some scenarios more acutely influenced by technological approaches to protect against climate impacts than measures aimed specifically to mitigate emissions. Thus, the 2°C scenarios do not necessarily have lower non-CO_2 emissions than the 4°C scenarios (Figure 2). Drawing together the quantitative and qualitative analysis addressing this complex set of interactions leads to the following insights:

1. Even when optimistic agricultural technology and consumption-related assumptions are combined within a 2°C scenario, reductions in UK consumption-based N_2O emissions are constrained to around 55% in per capita terms, compared with >90% cuts considered feasible for CH_4.
2. There are more opportunities for cutting CH_4 than N_2O on a per capita basis (not limited to agriculture [76]).
3. Reductions in meat consumption lowered per capita non-CO_2 emissions but the emissions cut is less evident when considering net savings across all food categories. This is in part because of the relatively extensive nature of UK livestock production compared with some other nations, coupled with a need for additional fertilizer for crops or vegetables substituting for a reduction in meat.
4. Extreme weather events, particularly if repeated over two or more growing seasons, have the potential to significantly reduce yields, disrupt sowing schedules and damage farming livelihoods. While UKCP-type climate impact assessments are useful for considering average change, they have less use in addressing more specific events that place potentially much greater pressure on farmers in maintaining or even improving efficient production. These weather events are also expected to lead to a rise in non-CO_2 as well as CO_2 emissions to maintain yields.
5. Technologies envisaged by stakeholders to 'adapt' farming to extreme weather events, such as indoor growing environments, could deliver a co-benefit in providing potential infrastructure for CH_4 or N_2O capture and/or processing. However, net savings depend on the emissions associated with animal feed production methods.

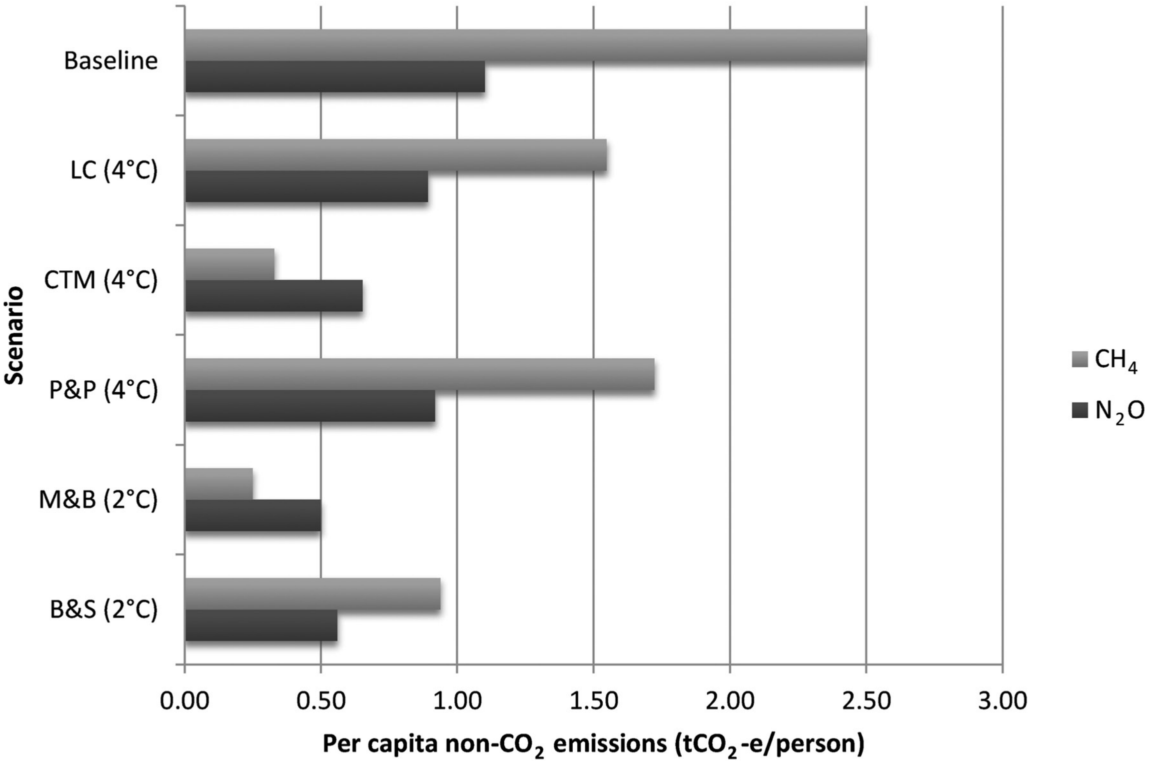

Figure 2. Scenario non-CO_2 per capita GHG emissions for a baseline year of 2004 and each scenario in 2050. Lab chop (LC), chicken tikka masala (CTM) and pasta & pesto (P&P) are the 4°C scenarios; mash & banger (M&B) and bubble & squeak (B&S) are the 2°C scenarios.

6. Practices that focus on improving the resilience of the existing agricultural system through diversification and intercropping are attractive when considering unpredictable impacts of extreme weather events, but may result in lower yields. This highlights a need to reduce waste in the supply chain where feasible.
7. The greater the proportion of food imported from regions without climate targets, the more challenging it becomes to mitigate in line with commitments to 2°C.
8. 4°C scenarios will be associated with major climatic impacts in the UK (particularly higher temperatures, more extreme weather events), which will have a significant effect on agricultural production processes and yields. Unless a radical shift in farming technologies and practices is assumed, it is expected that UK yields will reduce.

Discussion

Upscaling the scenarios to explore global non-CO_2 emissions

The greatest value in terms of participatory scenario development is the process itself, enabling rich debate with expert stakeholders and academics that provides a space where barriers and opportunities for realizing transformational change can be identified. The UK-focused scenarios therefore offer a contextual understanding of the evolution of non-CO_2 emissions by 2050 under a range of interacting drivers and constraints. These scenarios are not idealized scenarios where all the 'best' technologies and practices interact, but rather plausible systems with internal consistency as verified through stakeholder engagement. By combining expert stakeholder opinion with current literature and quantitative analysis on mitigation and adaptation in the food system, the insights can be taken a stage further to conduct an informed thought experiment to explore potential levels of non-CO_2 emissions at a global scale.

To do this, nations are combined into two regions: Annex B and non-Annex B. The per capita non-CO_2 emissions start at either Annex B or non-Annex B average 2004 levels (Table 1) respectively, transitioning towards an equal per capita non-CO_2 emission figure based on the bottom-up UK scenarios by 2050. Then, using median UN population growth projections, absolute emissions pathways are derived (Figure 3). This simple illustration assumes that the future UK non-CO_2 emissions, realized within the UK-focussed scenarios, become globally reproduced by 2050. In the

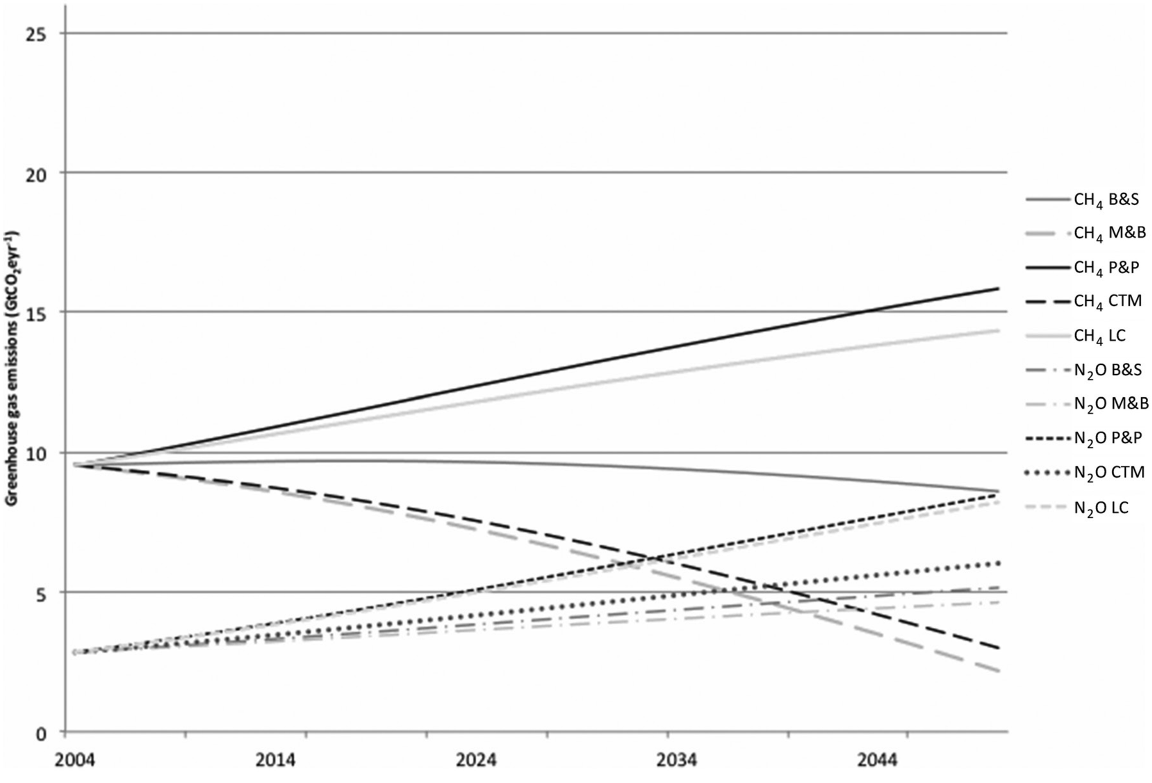

Figure 3. Global absolute N_2O and CH_4 emissions up-scaled from the UK-focused scenario analysis. B&S: bubble & squeak; CTM: chicken tikka masala; LC: lab chop; M&B: mash & banger; P&P: pasta & pesto.

Table 2. Implications for global non-CO$_2$ emissions if changes envisaged in the UK scenarios play out globally, assuming UN population growth projections.

Changes in emissions between 2004 baseline and 2050	B&S		M&B		P&P		CTM		–LC	
	N_2O	CH_4	N_2O	CH_4	N_2O	CH_4	N_2O	CH_4	N_2O	CH_4
Per capita	+27%	–37%	+14%	–84%	+109%	+16%	+48%	–78%	+102%	+5%
Absolute	+81%	–10%	+63%	–77%	+198%	+66%	+112%	–68%	+189%	+50%

B&S: bubble & squeak; CTM: chicken tikka masala; LC: lab chop; M&B: mash & banger; P&P: pasta & pesto.

case of the 2°C scenarios, absolute non-CO$_2$ emissions from Annex B and non-Annex B nations combined in 2050 are 6.8 and 13.7 Gt CO$_2$-e per year. For the 4°C scenarios, figures range from 9.0 to 24.3 Gt CO$_2$-e per year, compared with around 12.4 Gt CO$_2$-e per year in the baseline year of 2004.

Whilst per capita and absolute CH$_4$ emissions reduce in most cases, N$_2$O emissions rise both in absolute and per capita terms in all scenarios, despite the inclusion of many interventions to mitigate emissions (Table 2 and Figure 3). Even in a scenario with around a 50% cut in per capita N$_2$O emissions in the UK, as in the case of B&S, there is a 27% per capita rise at a global level compared with the 2004 baseline (because the UK's per capita consumption emissions start higher than the global average). When combined with rising population, this leads to an increase of 81% in global absolute N$_2$O for that same scenario.

Comparison with scenarios literature

Given the nature of the 'upscaling' process to infer global non-CO$_2$ emissions, it is important to consider the plausibility of the levels of per capita emissions derived and also to compare the results with those in the literature. Firstly, it should be noted that while the non-CO$_2$ emissions derived from the UK-based scenarios were used as a 2050 equal per capita endpoint for all nations, this does not imply that UK consumption patterns are assumed globally. Rather, a combination of consumption change, climate change as well as shifts in agricultural production systems underpin the per capita non-CO$_2$ value assumed for 2050. Using data from the FAO for agricultural non-CO$_2$ emissions for Annex 1 and non-Annex 1 nations (there are only minor differences between Annex 1 and Annex B categorizations), Figure 4 illustrates that while reductions in N$_2$O and CH$_4$ emissions have stabilized in recent years for Annex 1 nations, non-CO$_2$ emissions for non-Annex 1 nations continue on an upward trend. On average, agricultural N$_2$O in non-Annex 1 nations is growing at slightly more than 2% per annum and CH$_4$ at 1.2%. Population growth over the same period was around 1.6% per annum. A continuation of this trend in the agricultural component of N$_2$O, for instance, would result in N$_2$O emissions reaching 3.8 Gt CO$_2$-e by 2050.

Assuming that within non-Annex 1 nations, there continues to be emissions of N$_2$O from the industry, transportation and energy sectors of a similar proportion to those released today (the proportion in Annex 1 nation is higher), the N$_2$O emissions by 2050 would reach around 4.8 Gt CO$_2$-e – a similar value to that assumed for the 2°C scenarios in Figure 3. Yet with population growth expected to reduce in terms of growth rate, this growth trend would, all things being equal, be expected to be lower than 2% per year. On the other hand, this extrapolation neglects the potential additional N$_2$O emissions associated with rising temperatures and disruption to agriculture that are argued to more significantly impact non-Annex 1(B) agriculture than in the richer nations. For instance, the release of N$_2$O emissions tends to be higher in less industrialized nations due to higher temperatures and use of more urea and ammonium bicarbonate based fertilizers [77]. Furthermore, increases in temperatures (due to climate change) in Annex B nations are generally expected to be higher than the global average increase of 2°C, and the impacts of severe weather events are already affecting agricultural yields. It is therefore considered that this simple extrapolation reasonably reflects plausible future levels of non-CO$_2$ in the context of warmer temperatures associated with a global 2°C rise.

There are a large number of global emission scenarios in the literature exploring both high- and low-mitigation futures leading to a range of climate impacts. Amongst those, the IPCC's Special Report on Emission Scenarios [78] gives a suite of scenarios that have subsequently underpinned a substantial body of work exploring how futures shaped by a range of socio-economic storylines impact the climate [47]. More recently, the RCPs [101] have coupled detailed modelling with narratives to describe four new global scenarios including one, RCP3PD, purposely developed to align with the global

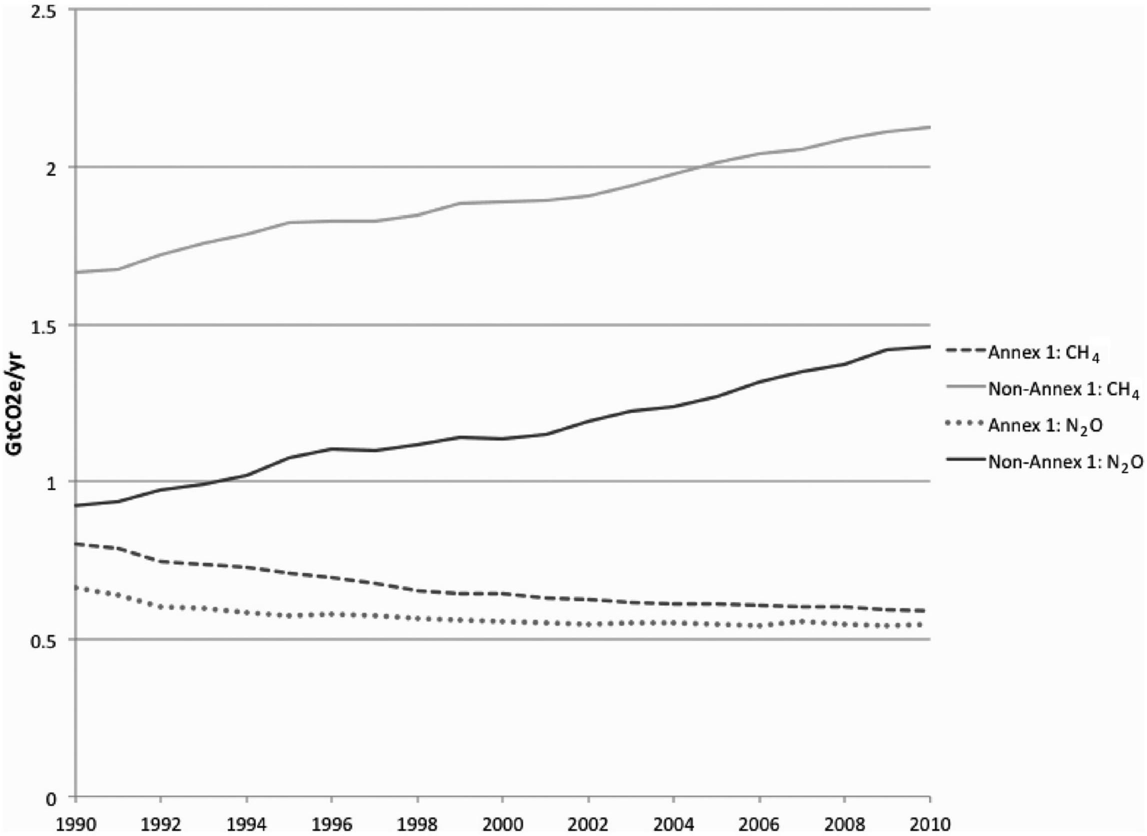

Figure 4. Agricultural N_2O and CH_4 emissions from FAO statistics broken down into Annex 1 and non-Annex 1 groupings. Data taken from [103].

ambition of avoiding a 2°C rise. This is in contrast to SRES, which were non-mitigation scenarios. The N_2O and CH_4 emission pathways from the RCPs are presented in Figure 5 to compare with the scenario-derived pathways from this analysis as presented in Figure 3. N_2O emissions within the RCPs rise to a maximum of around 6 Gt CO_2-e year^{-1} by 2050 and a minimum of just below 3 Gt CO_2-e year^{-1}, in contrast to the bottom-up analysis in this paper where all scenarios have higher N_2O emissions by 2050, ranging from 4.6 to 8.5 Gt CO_2-e year^{-1} despite the stakeholders and researchers visioning some futures with what they considered to be very significant mitigation. For the CH_4 emissions, the RCP range includes a scenario with considerably higher CH_4 emissions than envisaged in this paper's analysis and more conservative lower end in terms of potential mitigation opportunities in contrast to an optimistic future for mitigation developed within this paper.

Davidson [13], in analysing the scale of changes necessitated by the RCP N_2O levels, concludes that the RCP N_2O range is technologically feasible if challenging due to socio-economic and political barriers. For example, he concedes that a 50% reduction in the meat consumption of industrialized countries is unlikely, given 'current cultural trends'[13, p. 5]. Nonetheless, his final conclusion that 'the RCPs … are reasonable projections of a range of scenarios' is at variance with the analysis within this paper. Assuming UN population growth projections, the RCP3PD scenario implies that a per capita N_2O emission level of 0.32 t CO_2-e per person is achievable by 2050, which is equivalent to a global 53% reduction in per capita N_2O from the RCP's 1990 baseline and below the EEMRIO baseline (2004) average in non-Annex B nations of 0.33 t CO_2-e per person (Table 1). Such levels of per capita N_2O are at present indicative of countries where agricultural efficiency and yields are well below those in wealthier parts of the world and many people are food insecure and undernourished with food consumption insufficient to support a healthy and balanced diet. Within non-Annex B nations, citizens consumed an average of 2600 kcal per day in 2005 compared with 3300 kcal in Annex B nations [16].

The RCPs present one of the few low-emission scenario studies detailing N_2O-related results as opposed to only focusing on aggregated GHGs and/

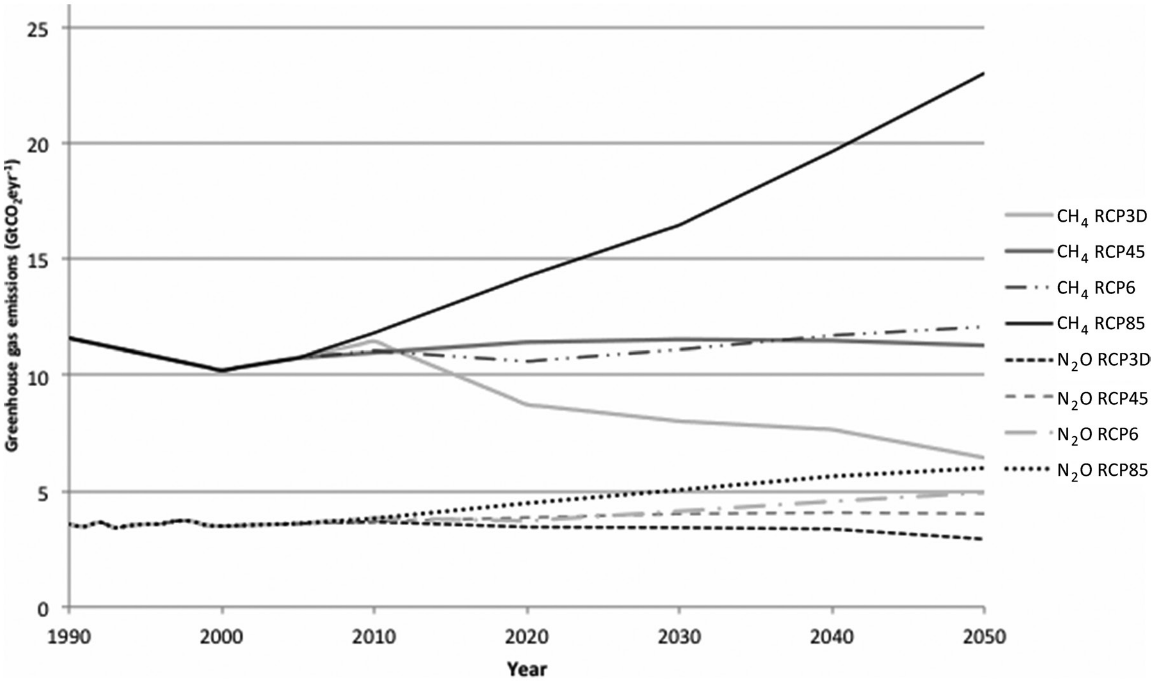

Figure 5. Absolute N_2O and CH_4 emissions from the representative concentration pathways (RCPs). Data taken from [79–84].

or non-CO_2 emissions. Most other scenario studies reviewed (that generally rely on integrated assessment modelling) report non-CO_2 bundled together with CO_2 and usually collectively reported as CO_2-e [85–89]. Amongst the few exceptions, even fewer studies explicitly disaggregate non-CO_2 emissions into CH_4, N_2O, F-gases, etc. [90–92], and yet fewer focus on the levels of mitigation assumed by the middle of the century (as opposed to 2100). Where N_2O is at least partly disaggregated and reported, its annual levels in 2050 are, at most, comparable to the lower end of the N_2O range calculated within this paper; in most cases, however, the N_2O levels by the middle of the century are assumed to be lower. For example, Rao and Riahi [90] estimate N_2O emissions in 2050 to be around 5.5 Gt CO_2-e year^{-1}, similar to levels discussed in this paper. On the other hand, Rao *et al.* [91] estimate N_2O emissions at about 2.2 Gt CO_2-e year^{-1} in 2050 in a strong mitigation scenario. Furthermore, Rao *et al.* [91] offer an overview of N_2O levels in a range of others studies, with N_2O in the two high-mitigation scenarios reducing to about 2.3–2.6 Gt CO_2-e year^{-1} by the middle of the century.

As forthcoming mitigation and adaptation literature is likely to draw extensively on the new RCPs, as it did with the SRES predecessor, their representativeness merits particular attention. The implied per capita N_2O emission cuts within the RCPs go beyond those reached using the scenarios in Table 2, where a reduction in the global average per capita N_2O level by 2050 is not considered feasible. With highly conservative projections limiting annual rises in global affluence (GDP per population) to just 1.5% per year, this would, through the use of the IPAT identity, suggest improvements in the emissions intensity of N_2O (t CO_2-e per unit of GDP) of 60% between 2010 and 2050. Given the constraints on N_2O reduction, the increasing severity and scale of the impacts of climate change and the anticipated growth in quality and quantity of per capita food consumption within emerging and developing economies, it is challenging to accept that the very low levels of N_2O emissions within the new RCPs are feasible over this time period. This is all the more questionable when placed in the context of contrasting expectations from the FAO [16] where global food production is expected to increase by 60% by 2050 compared with 2005. Accessing this level of rise in food production would, according to the FAO, require a 58% increase in fertilizer application over the same period. And this is before considering how climate change can lead to further increases in emissions through measures taken to adapt agricultural systems to crop failure or build resilience. The absence of analysis that considers the impacts of rising temperatures and extreme weather

Key terms

Emissions floor: The level below which it is considered infeasible to reduce GHG emissions.

events on levels of future N_2O emissions, including in the most recent UNEP report [93], is a notable gap in the literature.

Implications for cumulative GHG emissions

As stated earlier in this paper, it is the cumulative emissions that dictate future temperature rises, shifting the policy focus from long-term emission reduction targets towards mitigation measures that can be realized in the short term (<10 years). This analysis suggests that the 2°C RCP scenario, RCP3PD, which will form the basis of many studies over the coming decade, has levels of N_2O emissions that are lower than expected from a bottom-up consideration of the drivers of N_2O, if including climate impacts. Drawing instead on the contextual analysis presented in this paper, the higher levels of N_2O postulated would consume more of the available cumulative emissions budget than in this case. RCP3PD's cumulative N_2O emissions are 136 Gt CO_2-e between 2010 and 2050, whereas in the two contextual scenarios associated with a 2°C temperature rise, cumulative emissions are 154 and 164 Gt CO_2-e (14–22% higher). Or, to put it another way, an additional 18–28 Gt CO_2-e would be unavailable for the other GHGs, including CO_2, over a 40-year timeframe from 2010 to 2050, placing additional pressure on the energy system and industrial processes, as well as sectors driving land-use change, to achieve greater decarbonization.

In contrast, RCP3PD's cumulative CH_4 emissions fall between the two 2°C scenarios developed here: one with cumulative emissions 12% higher and one 27% lower for the period 2010–2050. Taking N_2O and CH_4 together, the 2°C scenarios developed are either 15% lower or higher than the cumulative budget of RCP3PD between 2010 and 2050.

Framing mitigation in cumulative emissions makes clear the interconnection between varying efforts to curb each GHG. This analysis emphasizes challenges in reducing global N_2O emissions given rise in population coupled with dietary shifts, rising levels of consumption, growth in fertilizer use and the impacts of climate change [61]. Unlike with CO_2 mitigation, where unproven negative emissions technologies are frequently relied upon within 2°C-type scenarios, constraints on reducing N_2O particularly lead to the existence of a non-CO_2 **emissions floor** or a level below which it becomes too challenging to cut emissions with known technologies and practices. This floor dictates both the timing and level of CO_2 mitigation, with a higher floor necessitating greater and more urgent reductions in the other gases. In all of the contextual scenarios, absolute N_2O emissions rise as a proportion of the total GHGs by 2050. Thus, although the global emissions floor reduces to just under 7 Gt CO_2-e by 2050 in the most stringent scenario in this paper, N_2O emissions in this analysis would be expected to increase post-2050 (Figure 5), assuming population continues to rise.

Limits to the extent of global non-CO_2 mitigation using scenario analysis are infrequently considered elsewhere, for example, Bowen and Ranger [92, p. 19] discuss a ' "stabilised floor" of around 4 to 6 Gt CO_2-e' in 2100 and a follow-up study on constraining global warming to a 1.5°C temperature rise with a 10–30% probability has a yet more ambitious GHG emissions floor of 0.3–3.4 Gt CO_2-e year^{-1} in 2100, [94, p. 9], with CH_4 and N_2O 'constituting a higher proportion [than CO_2]'[94, p. 7]. Two other studies postulate an emissions floor of 6 [95] and 7.5 Gt CO_2-e year^{-1} [96], respectively, but they do not reflect on how this could be achieved. Within the RCPs, N_2O and CH_4 combined in the 2°C RCP3PD are around 6 Gt CO_2-e year^{-1} by 2050 comparing well with these other studies as well as this paper's analysis. However, when considering N_2O and CH_4 separately, this analysis suggests that there are more constraints on curbing N_2O emissions, and greater potential for cutting CH_4 as a result of the larger share of N_2O associated with agriculture, as well as technical constraints on its mitigation.

Finding ways of reliably reducing non-CO_2 emissions will become increasingly pressing as global demand for food rises. A wide range of feasible CH_4 mitigation options were put forward by stakeholders, taken from the literature and quantitatively assessed during the scenario process, providing evidence for greater scope for achieving substantial CH_4 mitigation than for N_2O. This, coupled with the much longer lifetime of N_2O compared with CH_4 as well as the influence of carbon cycle feedbacks in raising the GWP of CH_4 from 21 to 34, highlights the critical importance of fully exploiting CH_4 mitigation potential whilst increasing the research effort towards developing agricultural systems that can minimize N_2O production. Trials to verify the efficacy of N_2O reductions across crop types in a range of climatic conditions are needed including assessments of how best to incentivize their use. Population growth, the desirable goal of improving the quality and quantity of food consumed within poorer nations and the necessity of using additional fertilizer to access higher yields will all drive up N_2O emissions even with improvements to agricultural efficiency.

Emissions driven by food consumption in one country often occur within another's borders. As many nations without binding climate change targets are providing Annex B nations' food for consumption and also have rapidly growing populations of their own to feed, greater attention is needed to full supply chains and systemic drivers of non-CO_2 emissions. For many Annex B nations, where consumption-based emissions are higher than territorial emissions, meaningful climate policies need to recognize the importance of the supply chain emissions, complementing mitigation efforts aimed at the emissions within their borders [4]. Furthermore, this raises the debate around levels of consumption in Annex B nations, given improving food security in non-Annex B nations is highly desirable.

Implications for managing and mitigating CO_2

CO_2 dominates annual emissions of anthropogenic GHGs and as a consequence receives the most attention within the emission mitigation literature. Here, instead, non-CO_2 is central to the analysis, with a particular focus on the food system. Nevertheless, it is precisely because CO_2 management is of crucial importance that a more in-depth account of non-CO_2, within a cumulative emission context, is necessary. The potential future share of non-CO_2 compared with CO_2 within carbon budgets is highly uncertain. By building a bottom-up understanding of the potential constraints on reducing non-CO_2 emissions, this paper sheds new light on the challenge for CO_2 mitigation and highlights a gap in the literature surrounding the impacts of climate change on levels of future non-CO_2 emissions.

Trade-offs between curbing non-CO_2 and CO_2 become apparent when exploring mitigation and climate impacts through the lens of the food system and in the context of a limited cumulative emissions budget. Arguably more pertinent to agriculture than energy systems are the direct impacts of climate change that can influence levels of CO_2 as well as non-CO_2 emissions. While within certain limits higher temperatures and rising CO_2 concentrations associated with an on-going rise in CO_2 emissions can offer improved conditions for plant growth, realizing yield potentials requires additional fertilizer leading in turn to a rise in N_2O emissions. Similarly, protecting crops and livestock against extreme weather events, or replacing lost agricultural product following a drought or flood, for instance, incurs an economic cost or damage, and with it additional GHG emissions: CO_2 associated with energy for the construction, heating and cooling of protected growing environments; additional fuel for machinery for replacement products; N_2O or CH_4 from replacement stock (if it is feasible within the time constraints of the growing cycle). Until there is a widespread decarbonized energy system that is able to support low-carbon agricultural production, the influence of climate change on the food system must be taken into consideration when setting and delivering on CO_2 budgets and targets.

The existence of a constraint on curbing non-CO_2 emissions is in stark contrast to the ambition placed on managing levels of CO_2, which, through technologies such as biomass with carbon capture and storage, is often assumed to have the capacity to fall to below zero during this century. Relying on negative emission technologies, which are yet unproven on a systems level, is arguably a dangerous and overly optimistic assumption to make. Furthermore, assuming the successful widespread deployment of these technologies relaxes the rate of CO_2 reduction required to remain commensurate with 2°C, providing a more positive and apparently achievable outlook to be communicated to policymakers. Softening the message for those in a position to decide on current and future mitigation efforts is not the role of scientists. Rather, the onus should be on the community to draw attention to constraints and barriers to cutting *all* GHG emissions in order that a more realistic appraisal of the challenge can be made and CO_2 management be more appropriately directed. The focus here on non-CO_2 reinforces other studies that identify the existence of an emissions floor, further emphasizing an urgent need to mitigate CO_2 emissions where it is most feasible and quickest to do so. The higher the non-CO_2 floor, the more rapidly CO_2 emission cuts are needed within the constraints of a chosen climate target. Conversely, relying on a low or non-existent emissions floor suggests a larger CO_2 budget is available, again relaxing the rates of mitigation for a chosen climate change target, delivering a more palatable but less realistic assessment of the climate change challenge.

Conclusion

Agriculture is more sensitive to climate impacts than many other sectors and its production levels are very closely associated with both population growth and the desirable goal of improving global food security. Overlooking the multiple emissions drivers in this complex system when devising mitigation policy can lead to overly optimistic assumptions of how deeply CO_2 and other GHG emissions can feasibly be cut [97]. Taking a systemic, bottom-up scenario approach to interrogating future levels of N_2O and CH_4 emissions reveals how, despite strong technological mitigation combined with changing patterns of consumption, a warming climate and growing population limit efforts to curb food system emissions. Exploring constraints on mitigating non-CO_2 emissions through a participatory stakeholder scenario approach, upscaled to illustrate potential implications globally, shows how difficult it is to envisage absolute non-CO_2 emissions falling below an ‘emissions floor’ of around 7 Gt CO_2-e $year^{-1}$. In particular, global N_2O emissions will continue to grow post-2050 in all scenarios developed here, even those with a strong emphasis on mitigation measures. This finding is at odds with the RCPs and a number of other low-emission scenarios, which in comparison assume that N_2O emissions can feasibly reduce by 2050. A continuation of absolute growth in global N_2O emissions, despite assuming optimistic mitigation has, because of cumulative emissions, direct implications for how urgently and deeply to cut both CO_2 and CH_4 for an assumed climate target.

Taking a consumption-based perspective is particularly useful when devising mitigation policy for addressing non-CO_2 because many Annex B nations import a high proportion of food. If non-CO_2 emissions are produced elsewhere to service national consumption, conventional policies targeting production within nation boundaries will have limited reach. This is even more critical when imports are from nations without climate targets. Non-CO_2 emissions are more directly impacted by climate change than energy-related CO_2. Coupling this with limitations on agricultural systems the world over, nations that are both signed up to avoiding 2°C and with the wherewithal to invoke supply chain influence to tackle emissions, should consider how best to do so. This may use conventional governance channels, employing, for instance, knowledge-transfer models, or equally through improving the sustainability of supply chains from consumption to production through the influence of multinational organizations. Using a consumption-based emissions approach allows for a more realistic appraisal of the scale of the 2°C challenge.

As energy systems become decarbonized, global non-CO_2 emissions largely associated with food consumption and production will increase in the share of annually produced GHGs. Emphasizing the importance of making cuts in food-related emissions highlights an urgent need for policymakers in Annex B nations to consider not only technological and supply-side interventions, but tackle the thorny issue of levels and types of consumption. Unlike large-scale infrastructure developments, measures tackling consumption and demand have the potential to cut emissions of CO_2 and non-CO_2 alike in the short term and could improve the diminishing chances of remaining within the carbon budget commensurate with the 2°C threshold.

Future perspective

The mitigation effort is most commonly directed at reducing CO_2 emissions from fossil fuel combustion. Whilst a transition to a decarbonized energy system by 2050 is considered feasible, if this becomes a reality, GHG emissions that prove more challenging to mitigate, such as N_2O, will become more prominent in the debate. This coupled with how rapidly the impact of extreme weather events can translate into a rise in food prices will all serve to raise the profile of the food system, its emissions and the need to build resilience in the agricultural sector. The question is 'how will the academic community respond to these developments?' As with many subject areas, researchers with expertise in agricultural processes are unlikely to be within the same research groups as those modelling climatic changes or considering energy system transitions. Yet, increasingly the research community needs to go beyond drawing on each others' expertise, further than multi- , trans- or cross-disciplinarity, to work in unison within co-located teams to design and develop research activity in a truly interdisciplinary manner.

The complexity of the food system, with its varied technical, environment, social and economic drivers and strong linkages to energy generation, water and land resources, would benefit greatly from an increase in interdisciplinary endeavour. This research suggests that couplings, for example, human development studies with agricultural biology or environmental engineering with sociology can more fully engage with the challenges posed around mitigating N_2O emissions than can single disciplines operating in silos. By bringing together these different perspectives, researchers will be better placed to tackle full supply chain emissions, including understanding their diverse drivers around the globe.

If the challenges posed by climate change are to be overcome, at least in part, a meeting of minds to define problems can offer new, much needed insights. This is already emerging in some quarters, with an increase in interest from research funders around the food–water–energy nexus as well as a rise in the number of researchers keen to engage in genuinely interdisciplinary activity. Of course disciplinary research may, out of necessity, continue to dominate, but the emerging expertise in interdisciplinary research needs support and encouragement given the extent of the systemic and complex challenges facing society.

The climate change challenge becomes ever more urgent each year, with time limiting the options available for mitigating emissions to be largely those that can deliver change in the short term. Perhaps with agronomists, biologists, engineers, political and social scientists working increasingly in single units, systemic 'solutions' to the climate challenge can be found. Specialists in demand and consumption require the same prominence in the portfolio of research endeavour as technologists, physical scientists and engineers. Only then will resilient options be derived and ultimately implemented in a timescale befitting of the scale of change facing society.

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Executive summary

Background and framing

- Diminishing chances of meeting the 2°C target stress the importance of developing emission mitigation strategies that consider climate adaptation and mitigation in unison.
- This is essential in the case of the food system, where the climate has direct impacts on agricultural production, with the relative high importance of non-CO_2 emissions compared with other sectors.

Data and methods

- A suite of UK-focused food system scenarios developed through a participatory backcasting approach, a cumulative-emission framing and a consumption-based emissions accounting framework is drawn upon.
- Quantitative modelling is coupled with iterative stakeholder engagement to assess the feasibility of model input assumptions, refine the quantification and generate plausible scenario narratives.
- Building on the UK food system scenarios, the potential scale and importance of non-CO_2 emissions are addressed globally.

Results

- Even when optimistic agricultural technology and consumption-related assumptions are combined within a 2°C scenario, reductions in UK consumption-based N_2O emissions are constrained to around 50% in per capita terms, compared with >90% cuts considered feasible by stakeholders for CH_4.
- Technologies envisaged by stakeholders to ‘adapt’ farming to extreme weather events, such as indoor growing environments, could deliver a co-benefit in providing potential infrastructure for CH_4 or N_2O capture and/or processing.
- The greater the proportion of food imported to the UK from regions without climate targets, the more challenging it becomes to mitigate in line with commitments to 2°C.

Discussion

- Global N_2O emissions continue to grow out to 2050 in all scenarios developed here, even those with a strong emphasis on mitigation.
- This finding is at odds with the new RCPs and a number of other low-emission scenarios, which in comparison assume N_2O emissions can feasibly reduce by 2050. The difference is largely attributable to the influence of climate change on non-CO_2 emissions.
- Trade-offs between curbing non-CO_2 and CO_2 become apparent when exploring mitigation and climate impacts through the lens of the food system and in the context of a limited cumulative emissions budget.

Conclusions

- The scenarios, upscaled to illustrate potential implications globally, show that it is difficult to envisage absolute non-CO_2 emissions falling below an ‘emissions floor’ of ~7 Gt CO_2-e $year^{-1}$.
- A continuation of absolute growth in global N_2O emissions, largely to improve global food security within a changing climate, has direct implications for how urgently and deeply to cut both CO_2 and CH_4 for an assumed climate target.

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Financial & competing interests disclosure

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Supplemental data

See supplemental data, Appendix Table 3, here.

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