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# Future warming from global food consumption

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Food consumption is a major source of greenhouse gas (GHG) emissions, and evaluating its future warming impact is crucial for guiding climate mitigation action. However, the lack of granularity in reporting food item emissions and the widespread use of oversimplified metrics such as $CO_2$ equivalents have complicated interpretation. We resolve these challenges by developing a global food consumption GHG emissions inventory separated by individual gas species and employing a reduced-complexity climate model, evaluating the associated future warming contribution and potential benefits from certain mitigation measures. We find that global food consumption alone could add nearly 1 °C to warming by 2100. Seventy five percent of this warming is driven by foods that are high sources of methane (ruminant meat, dairy and rice). However, over 55% of anticipated warming can be avoided from simultaneous improvements to production practices, the universal adoption of a healthy diet and consumer- and retail-level food waste reductions.

Food is both an essential aspect of life and a considerable source of greenhouse gas (GHG) emissions. The agriculture sector is responsible for nearly half of methane ($CH_4$) emissions, two-thirds of nitrous oxide ($N_2O$) emissions and 3% of carbon dioxide ($CO_2$) emissions from human activities worldwide[1–4]. These three GHGs account for 80% of today's gross warming (29, 5 and 46%, respectively)[1], suggesting that agriculture may be responsible for approximately 15% of current warming levels. However, only one-third of countries reference agriculture mitigation measures in nationally determined contributions to the Paris Agreement[5]. To encourage more commitments to decreasing GHG emissions from food systems and support effective policy design, it is important to improve understanding of the role of global food consumption in contributing to future warming.

The challenge in estimating the warming impact of the agriculture sector is its emission of multiple GHGs with widely varying radiative properties, atmospheric longevities and emission sources[1,6]. Carbon dioxide, a gas that can last for hundreds of years in the atmosphere, is emitted throughout the food supply chain from sources such as energy use from cultivation machinery and product transportation. Methane, a gas able to trap more than 100 times more heat than $CO_2$ for equal mass but with an atmospheric lifetime of around a decade[1], is emitted primarily from the production of animal products and rice, through enteric fermentation, manure management and rice paddy methanogenesis. Nitrous oxide can trap over 250 times more heat than $CO_2$ by mass, lasts around a century[1] and is emitted through synthetic fertilizer use, the cultivation of nitrogen-fixing crops and ruminant excretion on rangelands.

To assess the warming impacts of agriculture that arise from these combined emissions, studies often use the simple metrics global warming potential (GWP) and its counterpart $CO_2$ equivalence ($CO_2e$) to estimate the impact of these gases on a common scale[7–13]. GWP quantifies the energy absorbed from a pulse of emissions of a non-$CO_2$ GHG relative to that of the same mass of $CO_2$ over a specified time horizon (for example, 100 or 20 years). $CO_2e$ uses the GWP as a multiplier to convert an amount of non-$CO_2$ emissions to the amount of $CO_2$ that would yield the same warming impact over a given timeframe. However, these metrics do not realistically convey climate impacts because they do not account for continuous and evolving emissions, do not calculate warming impacts over time and require the selection of an arbitrary time horizon that ultimately skews the climate impacts of either short- or

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long-lived GHGs[14]. For example, the most common time horizon is 100 years, which masks methane's true potency by considering several decades in which methane is no longer influencing the climate.

While alternative metrics have been proposed to improve the quantification of methane's impacts[15–18], none are without shortcomings[19–21] and climate modelling is still a superior method for assessing temperature impacts of GHG emissions over time. Of the studies that do go beyond simple metrics and estimate the warming impacts of food consumption using climate models, only select food items or food groups (such as beef and livestock) have been analysed[22,23]. A more comprehensive analysis that investigates the warming impact of all food sources is needed because it will: (1) improve understanding of how food consumption contributes to climate change in the near and distant future; (2) make clear the relative importance of different foods and gases in contributing to climate change; and (3) provide guidance for climate mitigation efforts in the food sector.

Therefore, in this analysis, we estimate the future warming impacts of sustaining current global dietary consumption patterns throughout the twenty-first century by using a reduced-complexity climate model. We develop a detailed inventory of individual GHG emissions from current food consumption based on an extensive literature review (Supplementary Table 1). We then scale annual emissions over time by gas based on a set of five population projections and model the impacts of these emissions on surface air temperature change using the reduced-complexity Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) version 6 (ref. [24]). We consider multiple population projections and attribute the climate impacts (via global mean surface air temperature change) to individual gases and food groups. Furthermore, we estimate how much future warming through 2100 may be avoided through demand- and supply-side interventions. These interventions are selected to reflect currently available mitigation strategies throughout the food supply chain and include realistic modifications to production practices[25,26], health-motivated changes to diets[27], decarbonization of the energy sector and decreases in retail- and consumer-level food waste.

## Results

Given that the most detailed, global-scale GHG emissions inventory covering the life cycle of a comprehensive list of individual food items reports emissions estimates in $CO_2$e100 (using GWPs with a 100-year time horizon[8]), we first disaggregated emissions into their individual GHG components ($CO_2$, $CH_4$ and $N_2O$) in order to input the emissions data into the climate model. We did this for 94 food items based on a literature review of 115 studies and a total of 206 estimations of the individual gas breakdowns for each food item or group (see Supplementary Table 1 for the emissions breakdown and system boundaries for each study). Present-day emissions were then calculated based on data outlining the food available for consumption for 171 countries from the Food and Agriculture Organization (FAO) food balance sheets[3] and summed over the global scale. Following the methodology of the FAO, food consumption here refers to the total mass of food available at the retail level, where food loss incurred throughout production and transportation has been removed. For a full overview of the inventory methodology, see the Methods.

### Global food consumption emissions by GHG

The total global annual GHG emissions for food consumption in 2010 were estimated as 4,860 million tonnes (Mt) $CO_2$, 151 Mt $CH_4$ and 9 Mt $N_2O$. These values are consistent with recent estimates[2,3,28,29], but are on the lower end of the range for $CO_2$ and on the higher end for $CH_4$ and $N_2O$. When combined using standard $CO_2$e metrics, our estimates (13 and 22 Gt for the 100- and 20-year GWPs (GWP100 and GWP20), respectively) fall within the ranges provided throughout the literature, which employ both a top-down and bottom-up approach for agricultural emissions accounting[8,17,30–33]. Potential differences may stem from the comprehensive food consumption data to which we apply emissions rates, the impacts of averaging the ratio of component gases over some food groups, differences in regional production methods and the inclusion of some life cycle assessments which cover slightly different production stages. For detailed comparisons with previous literature, see the Supplementary Discussion.

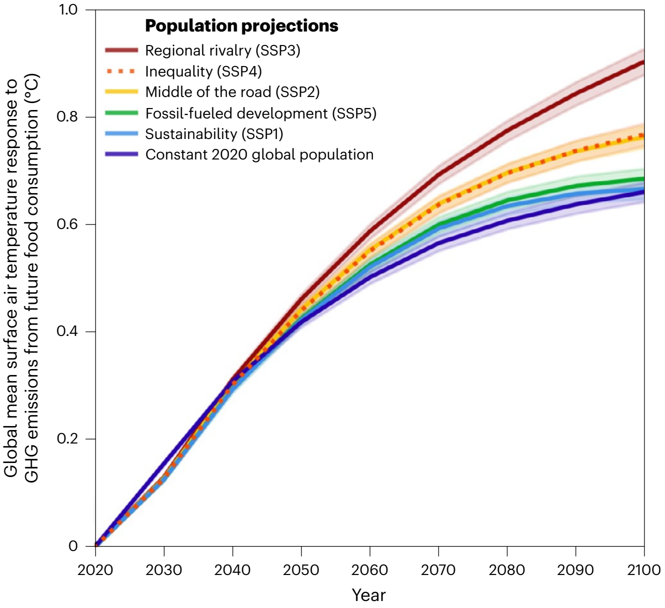

**Fig. 1 | Global mean surface air temperature responses to GHG emissions from future food consumption based on five population projections.** GHG emissions (carbon dioxide, methane and nitrous oxide) from food consumption were calculated using the database developed herein and the population projections developed for the following SSPs, as outlined by Riahi et al.[57]: Regional Rivalry, Inequality, Middle of the Road, Fossil-Fuelled Development and Sustainability (corresponding to SSP3, SSP4, SSP2, SSP5 and SSP1, respectively). The future warming associated with consumption from a constant 2020 global population is also provided for reference. RCP8.5 emissions were input for all sectors other than agriculture and all forcers other than carbon dioxide, methane and nitrous oxide to develop all-forcing baseline simulations from which the isolated food consumption temperature responses were derived (see Extended Data Fig. 1 for the results using RCP4.5 emissions). The shading represents 95% confidence intervals based on 190 ensemble members and the lines represent the mean of these ensemble members. The Inequality (SSP4) scenario is identified by a dotted line to better visualize overlapping results.

### Projected warming from business-as-usual food consumption

Using these individual GHG emissions trajectories as model inputs, we found that should current dietary patterns and agricultural production practices continue through the end of the century, global food consumption alone could contribute between 0.7 ± 0.2 and 0.9 ± 0.2 °C above present-day warming levels, depending on the population growth trend (Fig. 1). As we had already reached more than 1 °C warming above preindustrial levels by 2021[1], this additional warming alone is enough to surpass the 1.5 °C global warming target and approach the 2 °C threshold established by the Paris Agreement (assuming that current warming from GHG emissions is largely irreversible in the near future; for example, Solomon et al.[34]). Methane is responsible for the majority of the projected increase, accounting for nearly 60% of the warming associated with food consumption by the end of the century. About 20% of the end-of-century warming is attributed each to $CO_2$ and $N_2O$ emissions (Fig. 2).

We aggregated the emissions from each food item into 12 food groups: grains, rice, fruit, vegetables, ruminant meat, non-ruminant meat, seafood, dairy, eggs, oils, beverages and other. We found that the

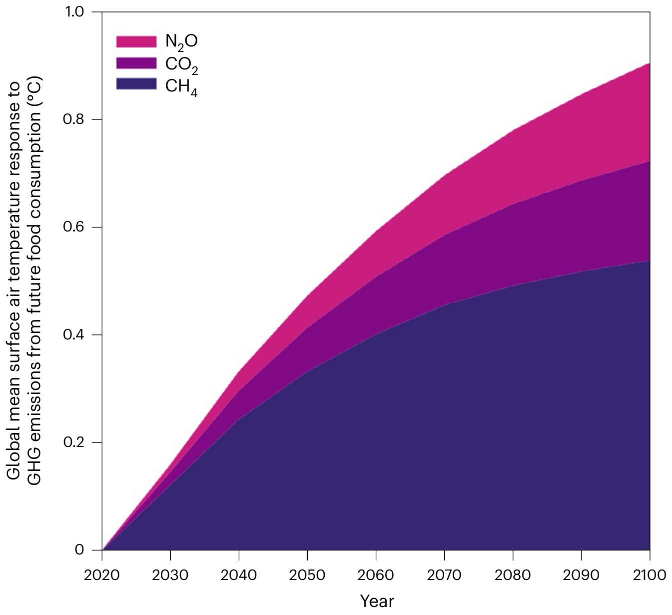

**Fig. 2 | Global mean surface air temperature responses attributed to individual GHG emissions (methane, carbon dioxide and nitrous oxide) from future food consumption under a high-population projection.** Population projections were taken from the SSP3 Regional Rivalry population growth scenario. The results shown are the means of a 190-member ensemble.

consumption of dairy and meat is responsible for more than half of the warming by the year 2030 and through to the year 2100 (Fig. 3). Of the other food groups, rice contributes to a large fraction of end-of-century warming (19%), whereas vegetables, grains, seafood, oils, beverages, eggs, fruit and all other uncategorized food items each contribute 5% or less. We note that the relative contribution of each food group towards end of century warming is distinct from their individual share of annual emissions in CO$_2$e20 and CO$_2$e100 (Extended Data Fig. 2). However, the dominance of meat, rice and dairy products towards the total climate impact of food consumption measured by each of these metrics is consistent.

Our study assumes that dietary patterns will remain constant through to the end of the century. However, the demand for ruminant meat is expected to increase by ~90% by 2050, while the consumption of all animal products is projected to grow by ~70%[35]. This growth far exceeds that proportional to projected population growth (an increase from 8 billion people to nearly 10 billion people by the midcentury), as future economic development around the world is expected to facilitate the purchase of more expensive goods such as meat and dairy items[36,37]. Therefore, given the relatively high emissions intensity of animal products compared with other food sources, our projected warming is likely an underestimate. Indeed, our estimates are lower than recently published literature estimating the future warming associated with livestock production[22,23] (for further details, see the Supplementary Discussion).

## Avoided warming from mitigation methods

There is, however, considerable potential for emissions mitigation through available modifications to production practices[9,25,26,29,37–41], consumption patterns[9,26,29,42–45] and food loss and waste[43,46,47]. Here we evaluated the amount of warming that could be avoided by pursuing efforts to decrease emissions from both supply- and demand-side interventions. We used the highest-population-growth scenario as our baseline, to quantify the upper end of potential climate benefits. Within each of the mitigation scenarios investigated, the choice of baseline population growth impacts the magnitude of avoided warming, but this magnitude is scalable, and the percentage decrease of future warming associated with each mitigation scenario remains roughly the same regardless of the assumed population growth pattern (Supplementary Table 2).

The first case we considered was improvement to production practices. We analysed emissions reduction potentials from improving the production processes associated with the four food categories that exhibit the highest relative contribution to warming: ruminant meat, rice, dairy and non-ruminant meat. Based on a recent comprehensive evaluation of available technologies, there are maximum potential decreases of roughly 35, 30 and 10% in total CO$_2$e100 emissions associated with ruminant meat, dairy and non-ruminant meat, respectively[26]. Mitigation options employed in these scenarios primarily concern the decrease of enteric methane emissions and manure methane and nitrous oxide emissions, although further reductions may be possible through mechanisms such as decreasing nitrous oxide emissions from the cultivation of animal feed. Rice exhibits the potential for a 50% decrease in methane emissions[25], although studies have suggested that the associated production changes could increase nitrous oxide emissions, which were not included here[40]. Similarly, we did not account for the development of new technology that could potentially decrease emissions or modifications to agricultural practices in response to changing local climates (for example, adapting to a changing climate by shifting crop locations). Our model simulations indicate that the immediate adoption of these production practices (emissions decreased linearly until full implementation by 2030) would avoid ~0.2 °C warming, or nearly one-quarter of the anticipated warming from food consumption by year 2100 (Fig. 4).

Consistent with international net zero emissions by midcentury goals, we also evaluated the warming reductions associated with food consumption should the energy sector be decarbonized by 2050. We found that this decarbonization of the energy sector would decrease end-of-century warming associated with global food consumption by ~17% or an additional 0.15 °C.

Next, we considered changes to dietary behaviours by analysing the potential avoided warming associated with the universal adoption of healthier diets. Previous studies have found that there may be synergies between actions associated with improving health and those associated with reducing GHG emissions intensity, and a health-driven mission may be more likely to be adopted on a global scale than changes in dietary behaviour in response to environmental concerns[12,36,37,42–45,48–50]. We used dietary recommendations provided by the Harvard Medical School, which focus on reduced meat intake, promoting a protein-rich diet with less saturated fat and cholesterol[27]. These recommendations specifically prescribe the sparing consumption of red meat (beef and pork; about one serving per week) and the limited consumption of fish, poultry and eggs (up to two servings each per day)[27]. We found that if these dietary changes were implemented globally, warming due to food consumption could be decreased by 0.19 °C by the end of the century, consistent with previous literature that has highlighted the potential for dietary recommendations to provide environmental as well as health benefits[42,45,48–50]. This amounts to ~21% of the anticipated warming due to sustained dietary consumption rates.

Behavioural change on a global scale is extremely complex, as dietary composition is often determined by culturally significant traditions or limited access to diverse food items (for example, Sobal and Bisogni[51]). In the mitigation scenario associated with implementing dietary recommendations, we modelled changes to the global average consumption rates, which resulted in decreases of animal product consumption in countries such as the United States and Spain while requiring increases in countries such as India and Ethiopia (see Extended Data Figs. 3–5). This suggested that implementing smaller dietary changes only in the regions currently dominating the consumption of high-emissions-intensity food items could equally decrease global emissions from food consumption. However, the intricacies of

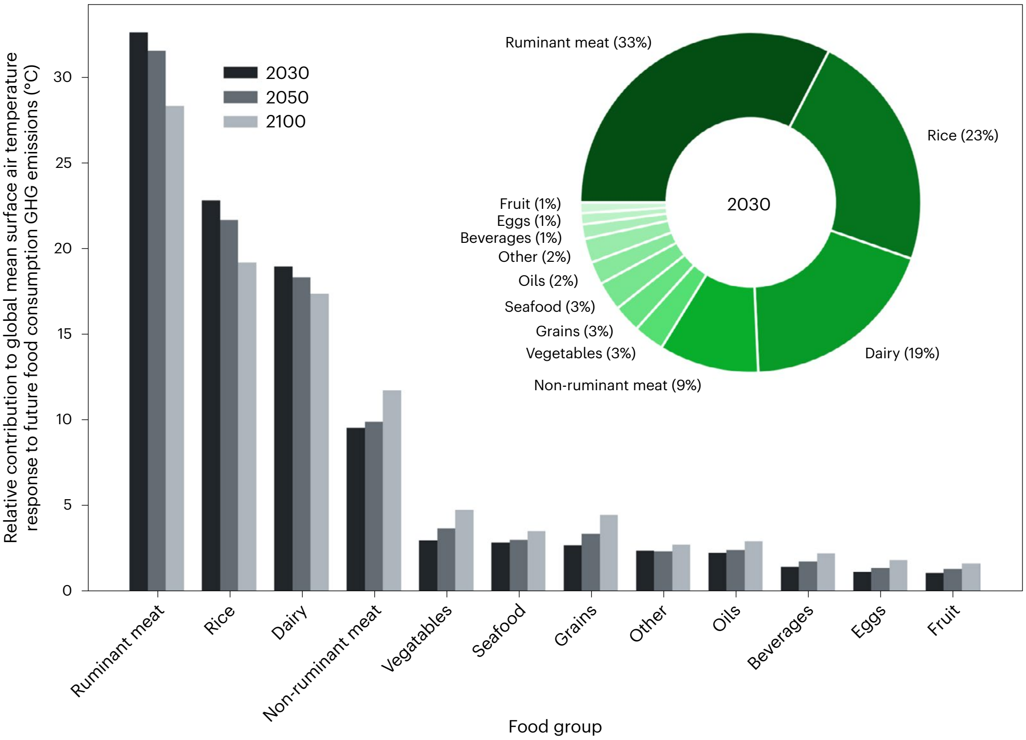

**Fig. 3 | Relative contribution of food groups to global mean surface air temperature responses to future food consumption GHG emissions under a high-population projection.** Contributions are presented for the years 2030, 2050 and 2100. The pie chart in the top right corner visualizes year 2030 percentage contributions. Population projections were taken from the SSP3 Regional Rivalry population growth scenario.

dietary composition choice limit how much of this mitigation potential is feasible or ethical to enact.

Finally, studies have also highlighted the potential for decreasing food loss and waste—at the farm, transport, retail and consumer level—as an avenue for decreasing agricultural GHG emissions[43,46,47,52]. Thus, we also explored the mitigation potential of decreasing retail- and consumer-level food waste by one-half, in line with the country-level pledges such as the *United States 2030 Food Loss and Waste Reduction Goal*[53]. We estimated food waste using the annex to FAOSTAT's food balance sheets[3,52,54], applying a regional average value per food group. If retail (consumer)-level food waste were cut in half, end-of-century warming would be decreased by 0.04 °C (0.03 °C), ~5% (4%) of the anticipated warming associated with dietary consumption. These reductions do not consider a decrease of food loss throughout the production chain, which could increase the overall reduction in warming substantially[47]. We were unable to assess this contribution as our underlying consumption data already excluded food lost throughout the farm and transport stages[3]. Based on global average estimates from the FAO, ~52% of food loss and waste occurs before the retail stage[54]. Were 50% reductions in food loss to be enacted through the production and transportation stages, we may expect an additional reduction in end-of-century warming on a similar scale (~0.1 °C).

Several studies have highlighted that multiscale approaches are needed for meaningful mitigation and that supply- and demand-side strategies should be adopted in tandem[8,41,55]. Should improved production practices, energy decarbonization, healthy diets and reduced food waste be pursued simultaneously with additive consequences, 0.5 °C of additional future warming may be avoided by 2100—more than 55% of the anticipated warming from sustaining global food consumption.

## Discussion

We found that sustaining current dietary patterns worldwide throughout the rest of the century could amount to nearly 1 °C of additional warming beyond today's level of ~1 °C above preindustrial times. Even under a range of population growth scenarios, we expect at least 0.7 ± 0.2 °C and up to 0.9 ± 0.2 °C of additional warming (under the Shared Socioeconomic Pathway 1 (SSP1) and SSP3 population projections, respectively). Either scenario would surpass the 1.5 °C temperature target from food consumption alone. Furthermore, with the increasing demand expected for animal products, we could see even more warming from food consumption than has been estimated here.

However, we also found that technologically available improvements to production practices, decarbonization of the energy sector, health-motivated changes in dietary habits and reductions in food waste could together decrease the anticipated warming by >55% compared with sustained dietary consumption rates, avoiding 0.5 °C relative to a business-as-usual baseline for a high-population-growth scenario. Further avoided warming potential lies within residual emissions that could be addressed by reductions in food loss throughout production stages or future technological innovations.

The key benefit of our approach in disaggregating GHG emissions from food consumption by gas is that it allows the use of a climate model to evaluate temperature responses to food consumption. This enables: (1) the quantification of food consumption's contribution to climate change over time; (2) the elucidation of the relative importance of different foods and GHGs in contributing to a future temperature increase; and (3) the identification of impactful mitigation efforts in the food sector. These insights are either not possible or not captured to the extent warranted by standard metrics (that is, GWP100 or $CO_2$e100) that undervalue methane's contribution to climate change. This bias is particularly critical since methane is responsible for the majority of future warming from the food sector.

For example, our analysis shows the dominance of methane emissions in contributing to future near- and long-term warming from food consumption: methane emissions account for 73% of the additional temperature increase from food by the midcentury and 60% by the

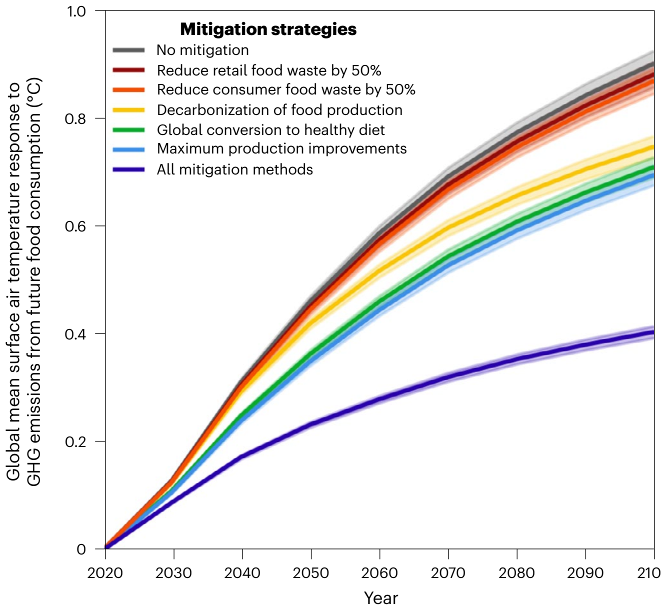

**Fig. 4 | Global mean surface air temperature responses to future food consumption GHG emissions for mitigation strategies and under a high-population projection.** Population projections were taken from the SSP3 Regional Rivalry population growth scenario. The scenarios include: (1) current dietary consumption patterns continued through to the end of the century ('no mitigation'); (2) a 50% decrease in retail-level food waste ('reduce retail food waste by 50%'); (3) a 50% decrease in consumer-level food waste ('reduce consumer food waste by 50%'); (4) full decarbonization of food production by the year 2050 ('decarbonization of food production'); (5) all people adopt a healthy diet as prescribed by the Harvard Medical School ('global conversion to healthy diet'); (6) technologically feasible production practice improvements are employed globally ('maximum production improvements'); and (7) all mitigation methods are employed simultaneously ('all mitigation methods'). The shading represents 95% confidence intervals based on 190 ensemble members and the lines represent the means of these ensemble members.

end of the century. Because methane emissions are relatively short lived and the ~30% of current warming attributed to methane is almost entirely from recent emissions[1], decreasing methane emissions can rapidly benefit the climate. The global rate of warming in the coming decades would slow[41], yielding societal benefits such as decreasing the probability of extreme weather and climate events[56].

Our analysis also indicates that >80% of future warming from food consumption will be from meat, rice and dairy products: notably high-methane food groups. Therefore, focusing on emissions reductions from the production, consumption and waste of these food groups can play a major role in avoiding a temperature rise associated with food consumption. Currently, about one-third (50 of 148) of updated Paris Agreement nationally determined contributions mention livestock mitigation measures and less than one-fifth (25 of 148) mention rice mitigation measures[5]. Our analysis provides motivation for more countries to prioritize actions to reduce agricultural GHG emissions.

Our results are impacted by several sources of uncertainty in the underlying data, such as standard uncertainties in the modelling of climate responses to GHG emissions and limitations in available GHG emissions data from individual food items. Future emissions will also be dependent on changes in consumption patterns and population growth. However, our analysis clearly demonstrates that current dietary production and consumption patterns are incompatible with sustaining a growing population while pursuing a secure climate future. Fortunately, compelling mitigation options are available to address this challenge.

## Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-023-01605-8.

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## Methods

We first built a comprehensive dietary emissions inventory (see Supplementary Data 1), which was developed by incorporating data from several different types of analyses. The life cycle emissions, in $CO_2$e100, from the production of individual food items (eggs, apples, pig meat and so on) were taken from Poore and Nemecek[8] and represent ~90% of global protein and calorie consumption. We matched these aggregate emissions estimates to consumption data from the FAOSTAT food balance sheets. When an exact match between food items in the two datasets was not available, we took weighted averages of the emissions associated with a representative food group or multiple food items, reflecting their relative reported consumption rates. We assessed the warming associated with the consumption of these food items by disaggregating the $CO_2$, $CH_4$ and $N_2O$ emissions from $CO_2$e values. In this analysis, the recorded $CO_2$e100 emissions were disaggregated via estimations of the ratio of component gases emitted throughout the production of each unique food item from a synthesis of the results of 115 peer-reviewed studies, resulting in 206 total estimations (Supplementary Table 1). All life cycle assessments identified were included in the literature review if they: (1) outlined the total emission of individual GHGs, including $CO_2$, $CH_4$ and $N_2O$; and (2) had a system boundary that at least covered the full food item production process. To retain as many studies as possible, in an effort to increase sample size and regional representation in our literature review, we retained studies with system boundaries that went beyond the farm gate. However, we note that most (96 of the 115) studies consisted of only on-farm emissions (cradle-to-farm gate), and that off-farm emissions (from packaging, transportation and retail) contribute a minor share of overall emissions. Studies whose boundaries surpassed the farm gate probably had a larger share of emissions associated with electricity and fuel usage, favouring higher-percentage contributions from $CO_2$ based on current global energy sources. This may mean that our results overestimate the emissions of $CH_4$ and $N_2O$ and their associated contributions to future warming. Our analysis accounts for the emissions associated with land use change, as the underlying $CO_2$e emissions used from Poore and Nemecek[8] include these emissions. We did not, however, adjust for land use change in the percentage breakdown of gas species. The extensive nature of this review demonstrates the need for better documentation of the emissions of individual GHGs within life cycle assessments. For more information about individual study boundaries, see Supplementary Table 1.

When available, the average of the percentage breakdown of individual GHGs for an individual food item was used. When at least one life cycle assessment study outlining this breakdown for a given food item was not available, the average across the associated food group was applied. Food item emissions were then scaled by current annual per-capita consumption patterns of 95 individual food items with global dietary consumption data on a country scale from the FAO[3], generating a country-scale database of current global dietary consumption emissions for all three major agricultural GHGs. This dataset was also aggregated into 12 categories, to distinguish between larger food groups.

We extrapolated this database through the end of the twenty-first century based on a range of population growth scenarios[57], assuming sustained dietary patterns. We then employed a prominent reduced-complexity climate model[24] to simulate changes in surface air temperature over the next century from anticipated global food consumption—in total and separated by GHG and by food group. Finally, we investigated how much future warming may be avoided through demand- and supply-side interventions, specifically through realistic modifications to production practices[25,26], health-motivated changes to diets[27], decarbonization of the energy sector and a 50% decrease in retail- and consumer-level food waste.

Our database provides consumption data in multiple units: kilograms of food per capita per year, grams of food per capita per day, grams of protein per capita per day and grams of fat per capita per day. While unit choice does not affect the estimate of the total GHG emissions produced by the consumption of each country, and by sum the world, it does provide versatility when using the database to consider the climate impacts of dietary choice. For example, the database allows us to compare the amount of emissions associated with adding 5 g of beef to per-capita daily consumption, or substituting the consumption of chicken for fish while maintaining the same daily caloric intake. This granularity of the database allows for a precise comparison of dietary choices that is not available or considered in other studies.

Our analysis anticipates a growth in GHG emissions associated with global food consumption proportional to that by population, assuming that dietary patterns remain constant. Annual emissions associated with current global dietary consumption patterns were extrapolated through to the end of the century, proportional to five population projections representing a range of future socioeconomic and demographic changes[57]. We also provide the warming proportional to a constant year-2020 global population for reference. Note that the percentage contributions from component gas emissions and individual food group consumption were estimated based on the warming impacts associated with the highest-population-growth scenario.

### Reduced-complexity climate model: MAGICC

The projected emissions were analysed through the use of a reduced-complexity climate model to directly estimate the temperature impact of food consumption. We employed MAGICC version 6. Extensive research has demonstrated model consistency with the sophisticated Coupled Model Intercomparison Project atmosphere–ocean and Coupled Climate–Carbon Cycle Model Intercomparison Project carbon cycle models[24], and today MAGICC is known for its reliability in modelling climate responses to small forcing changes[24,58].

The MAGICC model pairs a hemispherically averaged upwelling–diffusion ocean coupled to a four-box atmosphere (one over land and one over the ocean in both the Southern and Northern Hemisphere) with a carbon cycle model (with an average equilibrium climate sensitivity of 3 °C). Historical radiative forcings (years 1765–2005) are determined from historical GHG concentrations[59], historical emissions of ozone precursors[60], prescribed aerosol forcings, land use historical forcings (National Aeronautics and Space Administration Goddard Institute for Space Studies model; http://data.giss.nasa.gov/) and solar irradiances[61]. From 2005–2100, radiative forcings depend on GHG emissions (carbon dioxide, methane, nitrous oxide, ozone-depleting substances and their replacements), tropospheric ozone precursor emissions (carbon monoxide, nitrogen oxides and non-methane volatile organic carbon), aerosol emissions (sulfate, black and organic carbon, sea salt and mineral dust) and the indirect effects of aerosols (both first and second).

The radiative efficiency of methane (accounting for both short- and longwave absorption) and its atmospheric lifetime, as well as the radiative efficiency the of tropospheric ozone are updated from the default MAGICC properties, to reflect recent updates to scientific understanding[28,57,62,63]. All other properties are as default. Uncertainties exist within the model associated with the field's current knowledge of climate and carbon cycle processes, radiative forcings and indirect aerosol effects. The various calibration methods used by MAGICC determine the best parameterization from a wide variety of sophisticated models, but inherent uncertainties within these more comprehensive models will be translated into MAGICC's results. The simplicity of MAGICC also requires that parameters are averaged over large spatial scales. Further details of the model uncertainties are discussed by Meinshausen et al.[24].

### Business-as-usual and mitigation scenarios

We ran 335-year integrations from 1765–2100 for a set of 50 different simulations. These simulations comprised 29 pathways associated with sustaining current dietary consumption patterns and 21 mitigation pathways based on potential production and consumption improvements. For future emissions from sectors other than agriculture, we used Representative Concentration Pathway 8.5 (RCP8.5) emissions data, but the climate impacts were subtracted out as described below. We generated a 190-member ensemble simulation to assess the most likely temperature outcomes for each emissions scenario. Several calibration parameters (for example, climate sensitivity, equilibrium ocean–land ratio, vertical thermal diffusivity and $CO_2$ fertilization factor) were adjusted to emulate 19 Coupled Model Intercomparison Project phase 3 atmosphere–ocean general circulation models and ten Coupled Climate–Carbon Cycle Model Intercomparison Project carbon cycle models.

The first 22 scenarios account for warming impacts due to: (1) all natural and anthropogenic forcings; (2–7) sustained food consumption rates based on five separate population projections and one constant population projection (for reference); and the isolation of (8) the carbon dioxide emissions from dietary consumption, (9) the methane emissions from dietary consumption, (10) the nitrous oxide emissions from dietary consumption, (11) total emissions from non-rice grain consumption, (12) total emissions from rice consumption, (13) total emissions from fruit consumption, (14) total emissions from vegetable consumption, (15) total emissions from ruminant meat consumption, (16) total emissions from non-ruminant meat consumption, (17) total emissions from seafood consumption, (18) total emissions from dairy consumption, (19) total emissions from egg consumption, (20) total emissions from oils consumption, (21) total emissions from beverage consumption and (22) total emissions from the consumption of all other uncategorized foods. As a sensitivity test, scenarios 1–7 were repeated using RCP4.5 emissions data for sectors other than agriculture, the results of which are presented in Extended Data Fig. 1. Under this emissions scenario, we found that the warming accumulated by the end of the century that was associated with each scenario was actually higher than its RCP8.5 counterpart. This was due to the fact that RCP4.5 is more sensitive to a given change in $CO_2$ emissions relative to RCP8.5, primarily because $CO_2$'s radiative efficiency has a logarithmic relationship with its concentration (generating a higher relative change in radiative forcing associated with lower background concentrations).

We also investigated six mitigation scenarios: (1) universal implementation of technologically feasible production improvements; (2) the global adoption of a healthy diet; (3) a 50% reduction in retail-stage food waste; (4) a 50% reduction in consumer-stage food waste; (5) full decarbonization of the electricity sector; and (6) the implementation of all five mitigation actions simultaneously. Each of these mitigation scenarios was run five times, assuming one of the five population growth scenarios.

The warming associated with the emissions of each scenario must be isolated from that associated with all natural and anthropogenic sources. We thus first subtracted the total emissions of all gases associated with each simulation from the total RCP8.5 emissions in the all-forcing scenario driven by all natural and anthropogenic forcings (equation (1)). The annual average mean surface temperature changes associated with these emissions profiles were subtracted from the temperature changes in the all-forcings scenario, to determine the contribution to future temperature change from each simulation (equation (2)). Each mitigation scenario was analysed independent of other potential mitigation efforts that may occur outside of the agriculture sector. The same methodology can be used to isolate temperature changes due to the emissions of individual gases or from the consumption of specific food groups.

$$\text{Emissions}_{\text{all forcings without simulation}} = \text{Emissions}_{\text{all forcings}} - \text{Emissions}_{\text{simulation}} \tag{1}$$

$$\Delta T_{\text{simulation}} = \Delta T_{\text{all forcings}} - \Delta T_{\text{all forcings without simulation emissions}} \tag{2}$$

## Potential sources of uncertainty

The regional composition of the global population is assumed to change with each population growth scenario. Specifically, the SSP3 scenario used as our baseline scenario exhibits the highest regional population growth rate in Asia, the Middle East and Africa. While the emissions intensities of the current diets consumed in these three regions are moderate to low compared with the rest of the globe, the extrapolation of current consumption and production data along these population projections reflects some economic and social factors. The effects of future trends in age or gender on a regional scale and how these factors may influence regional GHG emissions associated with diet were not considered.

In this analysis, we only assessed the mitigation potential for emissions from food waste at the retail and consumer stage, as we intended to measure the future contribution to warming from direct dietary consumption. The mass of each food item reported in the FAOSTAT database does not include the mass of food lost throughout the production chain up to the retail stage, and retail- and consumer-level food waste was estimated via the annex to FAOSTAT's food balance sheets to calculate potential emissions reductions for the associated mitigation scenario[3,54]. This application of an average food waste rate across items within a food group and countries within larger regions is a source of uncertainty within this study. Further development of studies concerning food waste rates across the globe will improve our ability to model these values.

This study also did not consider the potential for land use availability to limit the future growth of food production. Recent literature has highlighted the range in land use associated with various diets and their viability as the global population continues to grow[8,12,36,64–66]. Potential future strain on land use demand associated with other societal needs, such as biofuel production, reforestation and commercial development, may necessitate a limit in the growth of dietary consumption.

Although life cycle assessments for the production of individual food items are vast in number, the literature is not representative of every production practice and reports often aggregate GHG emissions into $CO_2e$ emissions. Various approximations are thus necessary in order to estimate the global GHG emissions from dietary consumption and the potential for mitigation using currently available data. The first source of uncertainty from these approximations is associated with the underlying $CO_2e$ emissions assigned to each food item. We applied the reported mean $CO_2e$ emissions from Poore and Nemecek[8] to every matching food item in the FAO food balance sheets, and where a direct match was not available we applied a weighted average reflecting global annual production rates to the set of food items most closely related to the food in question. While this method provides a best estimate of the emissions associated with the global production of a food item, it does not account for individual farm idiosyncrasies or the relative intensity of one production method over another, which have been shown to impact the estimations of total GHG emissions associated with food items[67]. We performed a sensitivity test to explore the range of uncertainty introduced through this method. We used the fifth and ninety-fifth percentiles in $CO_2e$ emissions for each food item available in Poore and Nemecek[8] to represent the lower and upper bounds of the uncertainty range, respectively, keeping all other steps in our methodology the same as for the baseline warming scenario using SSP3 population projections. This range in $CO_2e$ emissions led to projections of the future warming associated with global food consumption ranging from 0.6 ± 0.02 to 2.3 ± 0.1 °C by the end of the century. This upper bound is inconsistent with future projections of global warming levels by the end of the century[1], reflecting the high upper bound in $CO_2e$ emissions recorded by Poore and Nemecek[8]. However, the reported confidence intervals are representative of the range of emissions that could occur for a specific food item, and were not designed to represent the range in emissions from that food item in the aggregate globally. This further motivated our choice to use the mean value for each food item's $CO_2$e emissions in our study. Improved documentation of life cycle assessments of more food items on a regional and local scale would help to decrease this source of uncertainty.

Another approximation in our methodology related to the percentage breakdowns in individual GHG emissions ($CO_2$, $CH_4$ and $N_2O$) estimated by our literature review. To fill gaps in the literature, we took an average of the individual gas emissions recorded by life cycle assessments associated with the production of each food item. When life cycle assessments for a specific food item listed in the FAO food balance sheets outlining the emissions of $CO_2$, $CH_4$ and $N_2O$ individually were not available, an average of the GHG emissions for the encompassing food group was applied. We performed another sensitivity test to evaluate this source of uncertainty. Using a bootstrap analysis, we randomly selected one GHG percentage breakdown from each food group (as outlined in Supplementary Table 1) and derived the total annual global GHG emissions from food consumption accordingly. We repeated this process 1,000 times and took the fifth and ninety-fifth percentiles in the total annual emissions of each gas to generate confidence intervals. We found that the confidence intervals for each gas were 4,018–6,554 Mt $CO_2$, 104–178 Mt $CH_4$ and 7–13 Mt $N_2O$. The upper bounds of these confidence intervals for $CH_4$ and $N_2O$ are slightly higher than the ranges published by recent literature, but the $CO_2$ emissions are in close agreement[2,3,28,29]. Overall, these confidence intervals are much smaller than those associated with the uncertainty discussed above from $CO_2$e emissions estimations from Poore and Nemecek[8] (3,046–12,879 Mt $CO_2$, 89–480 Mt $CH_4$ and 6–28 Mt $N_2O$).

Finally, the production-stage mitigation potentials for the high-emissions food groups identified in this study are presented as a mean of estimates outlined in a global-scale report from the FAO in 2013[26]. This averaging required to calculate global mitigation potentials does not account for the differences in mitigation options at the individual farm scale, but can be considered a storyline approach to estimating the scale for future warming reductions associated with production-level action.

## Data availability

The dietary consumption GHG emissions inventory is included as Supplementary Data 1. Results from the MAGICC model are available from the corresponding author upon request.

## Code availability

The MAGICC v6 executable model is available for download at http://www.magicc.org/download. The user manual can be accessed at http://wiki.magicc.org/index.php?title=Manual_MAGICC6_Executable. Full model details can be found in Meinshausen et al.[24]. We update the default radiative efficiencies of methane and tropospheric ozone and the atmospheric lifetime of methane to values in Myhre et al. (2013)[68] and derived from Etminan et al. (2016)[62].

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## Author contributions

C.C.I. and I.B.O. designed the experiments. C.C.I. and T.S. performed the experiments. C.C.I., I.B.O., T.S. and D.R.G. prepared and edited the manuscript.

## Competing interests

The authors declare no competing interests.

## Additional information

**Extended data** is available for this paper at https://doi.org/10.1038/s41558-023-01605-8.

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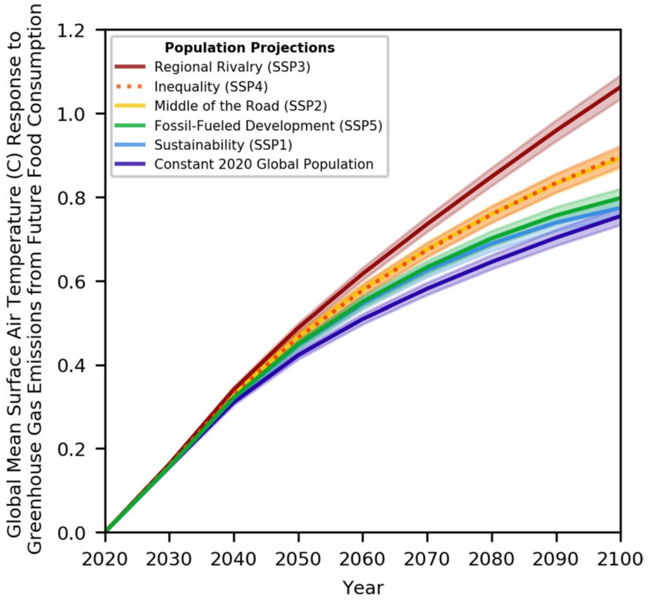

**Extended Data Fig. 1 | Global mean surface air temperature responses to greenhouse gas emissions from future food consumption based on five population projections for RCP4.5 emissions inputs for all other sectors and forcers.** Temperature responses expressed in degrees Celsius. Greenhouse gas emissions (carbon dioxide, methane, and nitrous oxide) from food consumption are calculated using the database developed herein and the population projections developed for the following Shared Socioeconomic Pathways (SSPs) as outlined in Riahi et al.[57]: Regional Rivalry, Inequality, Middle of the Road, Fossil-Fueled Development, and Sustainability (corresponding to SSP3, SSP4, SSP2, SSP5, and SSP1, respectively). The future warming associated with consumption from a constant 2020 global population is also provided for reference. RCP4.5 emissions were input for all sectors other than agriculture and all forcers other than carbon dioxide, methane, and nitrous oxide in order to develop all-forcing baseline simulations from which the isolated food consumption temperature responses were derived. See Fig. 1 for results using RCP8.5 emissions. Shading represents 95% confidence intervals based on 190 ensemble members and lines represent the mean of these ensemble members. Inequality (SSP4) scenario identified by dotted line in order to better visualize overlapping scenarios.

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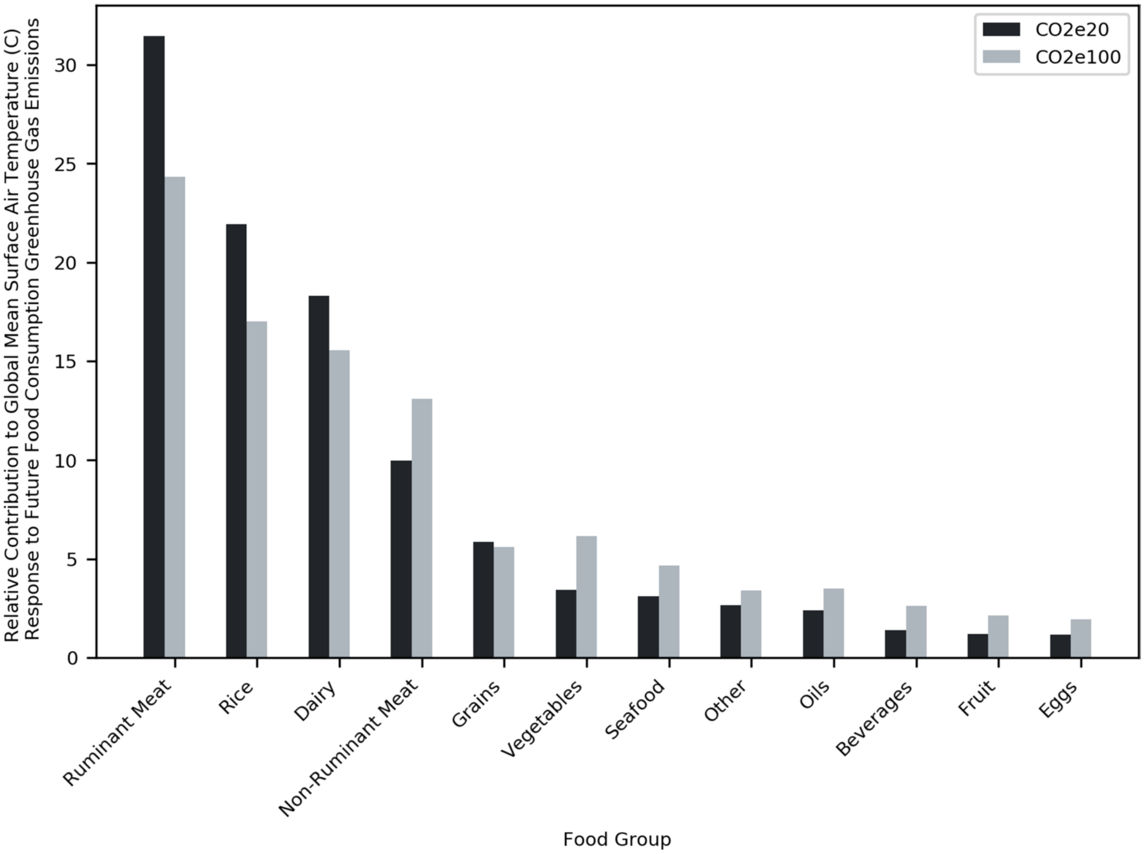
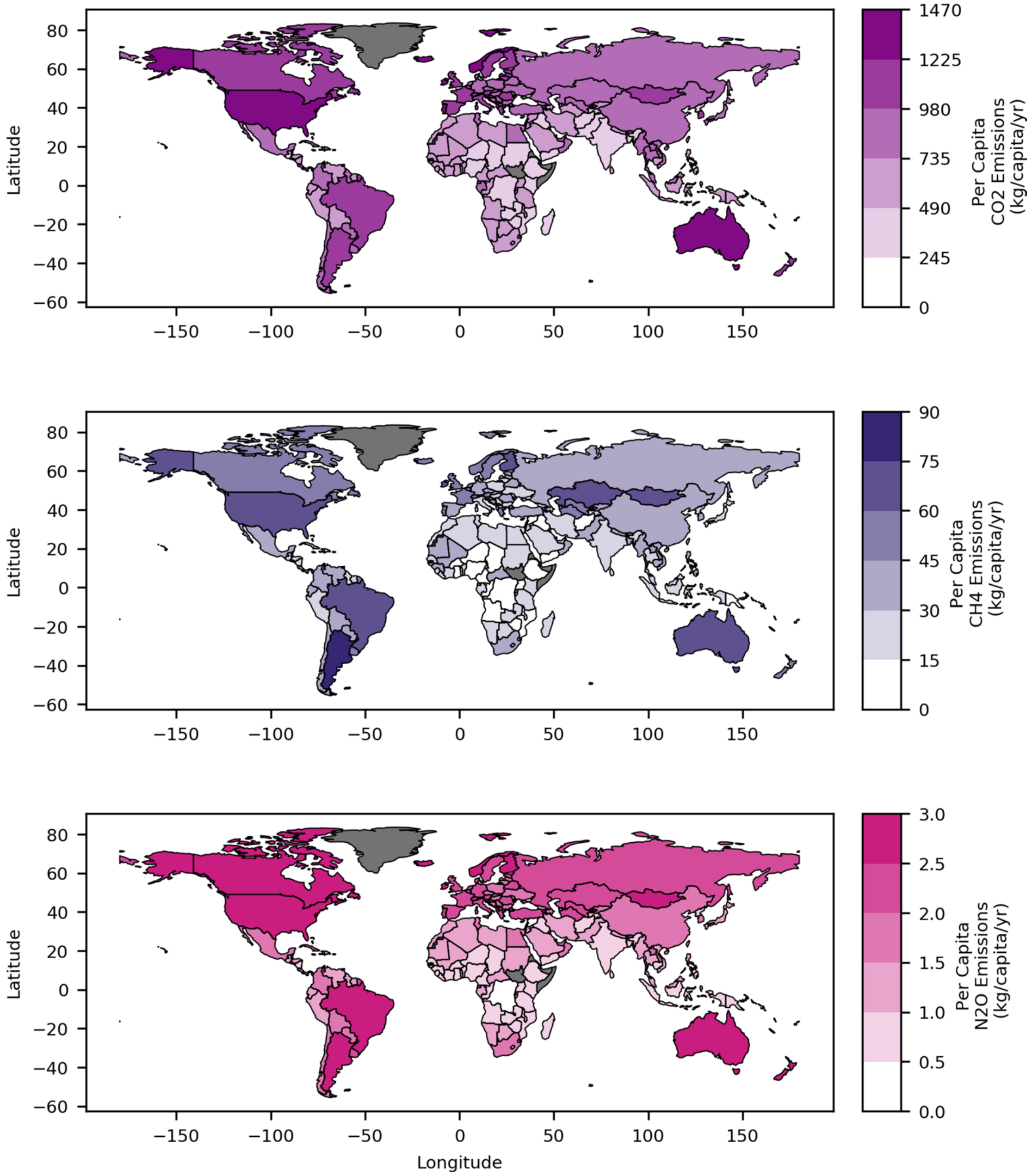
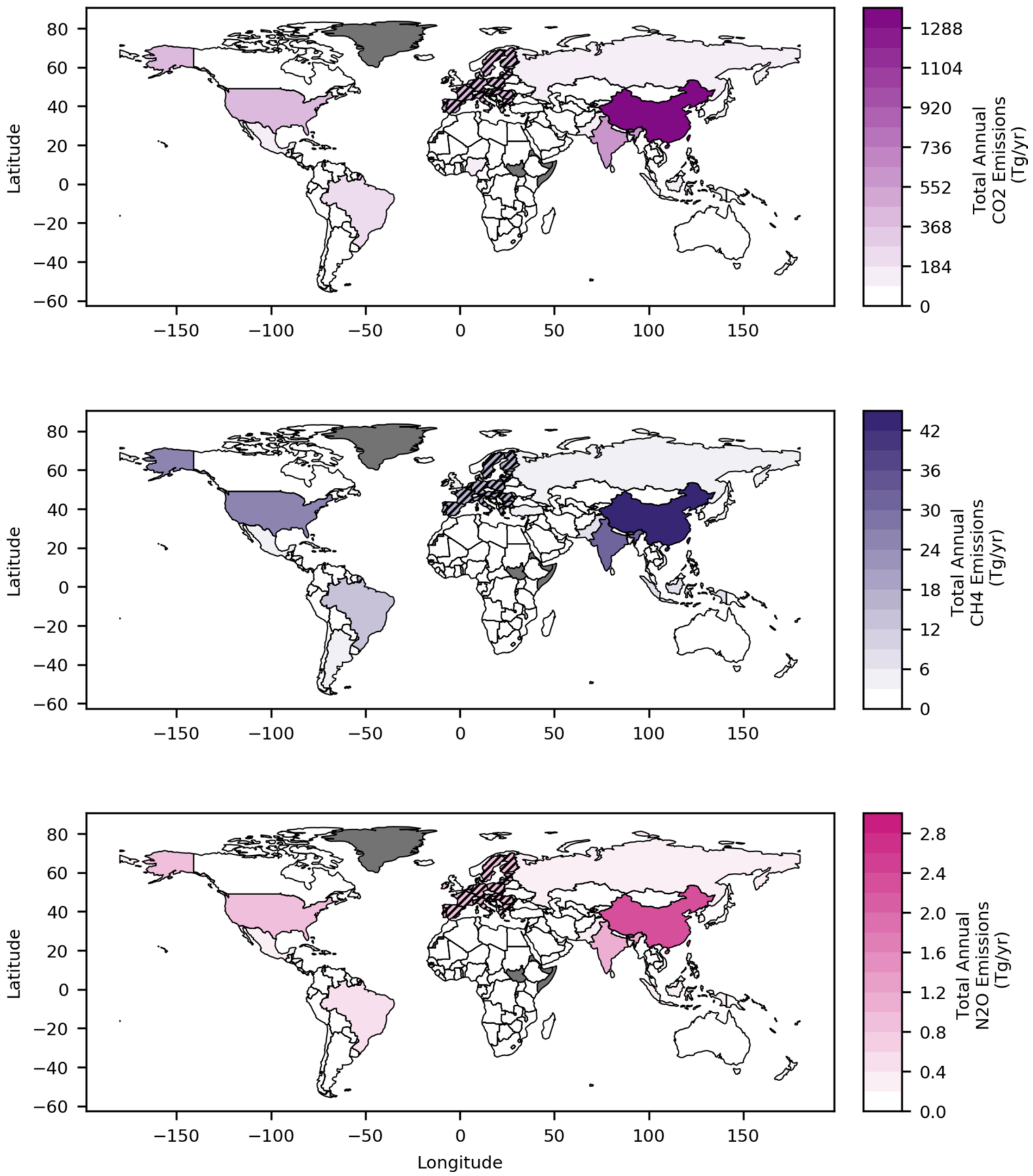


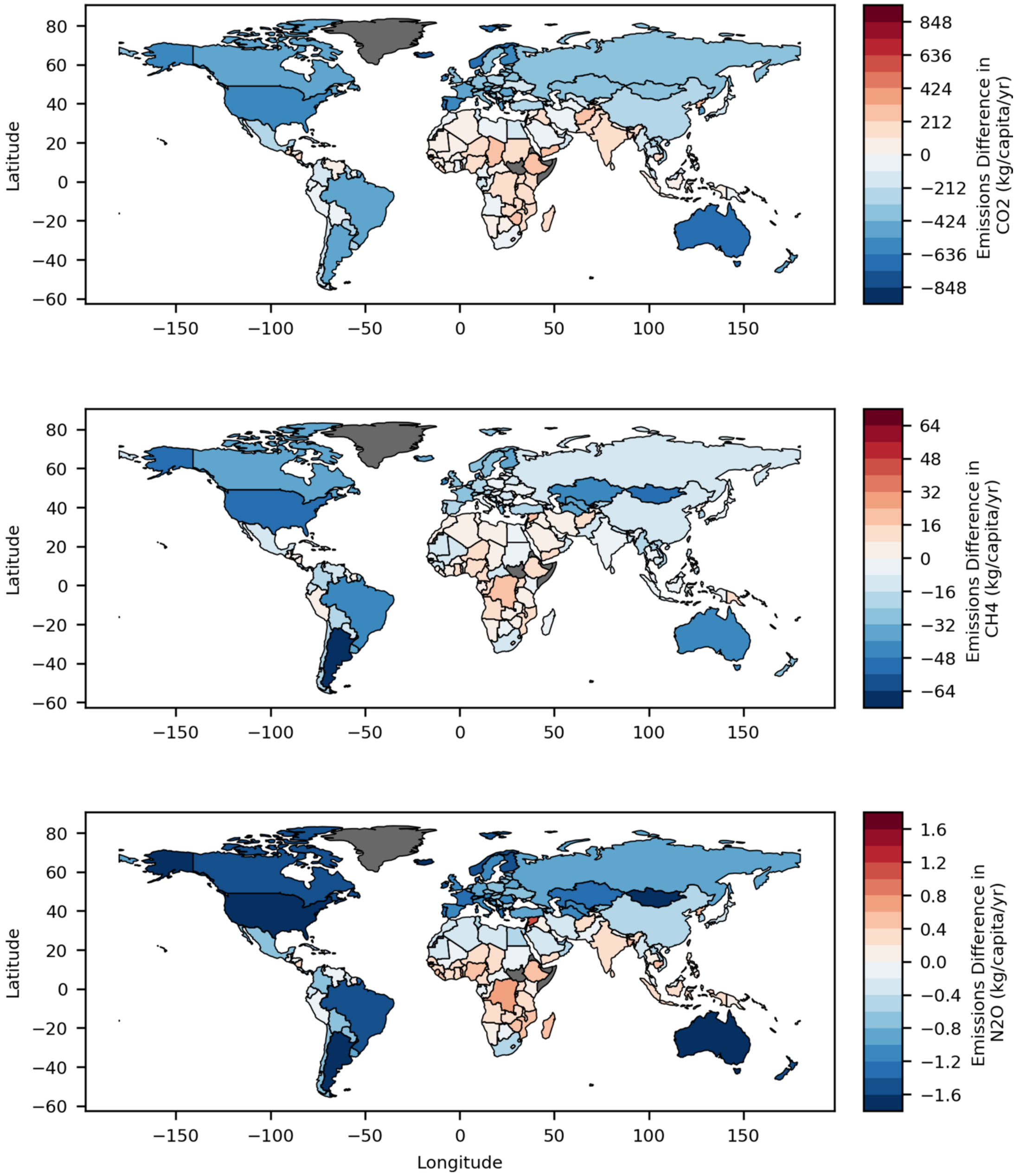
**Extended Data Fig. 2 | Relative contribution of food groups to future warming from food consumption greenhouse gas emissions measured using annual emitted carbon dioxide equivalence for 20- and 100-year time horizons.** Global warming potentials used for methane and nitrous oxide in the calculation are taken from IPCC AR5 and include climate-carbon feedbacks. Population projection taken from the SSP3 'Regional Rivalry' population growth scenario.



**Extended Data Fig. 3 | Estimated annual greenhouse gas emissions per capita from present-day food consumption for carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$) by country.** Emissions measured in kg gas/capita/yr. Countries without data colored in grey.



**Extended Data Fig. 4 | Estimated total annual greenhouse gas emissions from present-day food consumption for carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$) by country.** Emissions measured in Tg gas/yr. Food consumption emissions for each greenhouse gas have been summed over the European Union, hatched in black. Countries without data colored in grey.



**Extended Data Fig. 5 | Change in estimated greenhouse gas emissions per capita from present-day food consumption after applying dietary recommendations mitigation scenario.** Emissions were measured in kg gas/capita/yr. Red (blue) indicates countries which would contribute more (less) greenhouse gas emissions should all people adopt the recommendations from Willet et al. 2017 on consumption of meat, fish, and eggs, and global mean dietary consumption rates across all other food items. Countries without data colored in grey.