Title: Global food system emissions could preclude achieving the 1.5°C and 2°C climate change targets

Authors: M. Clark[1*], N. Domingo[2], K. Colgan[2], S. Thakrar[2], D. Tilman[3,4], J. Lynch[5], I. Azevedo[6,7], J. Hill[2]

Affiliations:

[1] Oxford Martin School and Nuffield Department of Population Health, University of Oxford, Oxford, United Kingdom.

[2]Department of Bioproducts and Biosystems Engineering, University of Minnesota, St. Paul, MN, United States.

[3]Department of Ecology, Evolution, and Behavior, University of Minnesota, St. Paul, MN, United States.

[4]Bren School of Environmental Science and Management, University of California, Santa Barbara, CA, USA.

[5]Department of Physics, University of Oxford, Oxford, United Kingdom.

[6]Department of Energy Resources Engineering Stanford University, Stanford, CA, United States.

[7]Woods Institute for the Environment, Stanford, CA, United States.

Abstract:

The Paris Agreement's goal of limiting the increase in global temperature to 1.5°C or 2°C above pre-industrial levels requires rapid reductions in greenhouse gas emissions. While reducing emissions from fossil fuels is essential for meeting these goals, other sources of emissions may also preclude their attainment. We show that even if fossil fuel emissions were immediately halted, current trends in global food systems would prevent achievement of the 1.5°C target and, by the end of the century, threaten achievement of the 2°C target. Meeting the 1.5°C target requires rapid and ambitious changes to food systems and all other sectors. The 2°C target could be achieved with less stringent changes to food systems, but only if fossil fuel and other non-food emissions are eliminated soon.

One Sentence Summary:

Rapid reduction of greenhouse gas emissions from the global food system is necessary to meet global temperature targets.

Main Text:

The goal of the Paris Climate Agreement is to limit average global temperature increases above pre-industrial levels to "well below 2°C" and to pursue efforts to "limit increase to 1.5°C". Achieving either goal requires rapid and dramatic reductions in greenhouse gas (GHG) emissions (*1*). To date, most efforts have focused on reducing GHG emissions from fossil fuel combustion in electricity production, transportation, and industry. Renewable energy sources, electric vehicles, improved efficiency, and other innovations and behavioral changes could eliminate most of these emissions, while carbon capture and sequestration could reduce atmospheric levels of previously emitted carbon. However, eliminating all emissions from these sectors may not be sufficient to meet the 1.5°C and 2°C temperature targets. The global food system is also a major source of GHG emissions, emitting ~30% of the global total (*2*, *3*). Nevertheless, reducing food-related emissions has received less attention, perhaps because they might seem to be an unavoidable environmental cost of feeding humanity.

The global food system generates GHG emissions from multiple sources. Major sources include land clearing and deforestation, which release carbon dioxide (CO_2) and nitrous oxide (N_2O); production and use of fertilizers and other agrichemicals, which emit CO_2, N_2O, and methane (CH_4); enteric fermentation during production of ruminants (cows, sheep, and goats), which emits CH_4; production of rice in paddies, which emits CH_4; livestock manure, which emits N_2O and CH_4; and combustion of fossil fuels in food production and supply chains, which emits CO_2. In total, global food system emissions averaged ~16 Gt CO_2eq yr^{-1} from 2012 to 2017 (*4*).

Here, we forecast GHG emissions from the global food system and assess whether they are compatible with the 1.5°C and 2°C targets. We forecast emissions as a function of per capita diets (what is eaten and how much), the GHG intensity of various types of foods (emissions per unit of food produced, as estimated through life cycle assessment), and global population size. We assume that food systems continue to transition along trajectories of the past 50 years (business-as-usual) (*5*, *6*). Our business-as-usual forecast makes straightforward assumptions: per capita dietary composition and caloric consumption continue to change as countries become more affluent (*5*); crop yields, which influence how much land is converted to cropland, increase along recent trajectories (*5*); global population increases along the United Nation's medium-fertility pathway (*7*); and the GHG intensity of foods (*8*) and the rates of food loss and waste (*9*) remain constant through time.

GHG emissions from the global food system occur largely from food production and when land is cleared for food production. Emissions from food production are calculated by pairing life cycle assessment estimates of the GHG emissions per unit of each type of food (*8*) with their forecasted total global demand, and include emissions from activities such as production of agricultural inputs, fertilizer application, and animal husbandry. Our estimates of emissions from supply chains do not include emissions from transportation, processing, packaging, retail, and preparation, which in total account for a minor fraction (~17%) of total food system emissions (*10*). Emissions from clearing land for food production are estimated by projecting crop yields, combining these with dietary projections to calculate annual rates of agricultural land-cover change, and pairing annual rates of agricultural land-cover change with IPCC Tier 1 estimates of GHG emissions from land clearing or carbon storage in biomass and soil following land abandonment (*11*, *12*).

We next determine the maximum allowable cumulative GHG emissions from all human activities from 2020 onwards that are compatible with having a 67% or a 50% chance of meeting the 1.5°C and 2°C targets, based on the IPCC Special Report on Warming of 1.5°C (*13*). We call these the "emissions limits". To incorporate CH_4 into the cumulative emissions framework accurately, we report emissions as GWP* CO_2 warming-equivalents (*14*), denoted as CO_2-we. We also show results with the more commonly-used GWP100 metric in the Supplementary Data. To have a 67% chance of meeting the 1.5°C and 2°C targets, the cumulative emissions limits are 500 and 1,405 Gt CO_2-we, respectively. For a 50% chance, the emissions limits are 705 and 1,816 Gt CO_2-we, respectively (see Supplementary Materials).

Our analysis suggests that reducing GHG emissions from the global food system will likely be essential to meeting the 1.5°C or 2°C target. Our estimate of cumulative business-as-usual food system emissions from 2020 to 2100 is 1,356 Gt CO_2-we (Fig. 1). As such, even if all non-food system GHG emissions were immediately stopped and were net zero from 2020 to 2100, emissions from the food system alone would likely exceed the 1.5°C emissions limit between 2051 and 2063 (date range reflects uncertainties in the 1.5°C emissions limit; see Supplementary Materials). Further, given our estimate of food system emissions, maintaining a 67% chance of meeting the 2°C target would require keeping cumulative non-food emissions to less than 50 Gt CO_2-we in total over the next 80 years. This is slightly more than one year of current GHG emissions from non-food system activities (*4*). Maintaining a 50% chance of meeting the 2°C target would allow for 455 Gt CO_2-we in total from non-food emissions, which is 9 years of current non-food emissions (*4*). These general trends hold even if emissions from fossil fuel use in the global food system itself were to be also immediately halted (see Supplementary Materials).

We next explore how global food system GHG emissions might be reduced through five strategies that target food supply and demand: (1) global adoption of a "plant-rich diet" (here modeled as a diet rich in plant-based foods that contains moderate amounts of dairy, eggs, and meat, such as a Mediterranean diet or planetary health diet (*15*)); (2) adjusting global per capita caloric consumption to healthy levels; (3) achieving high yields by closing yield gaps and improving crop genetics and agronomic practices; (4) reducing food loss and waste by 50%; and (5) reducing the GHG intensity of foods by increasing the efficiency of production, such as by altering management regimes (e.g., precise use of nitrogen fertilizer and other inputs) or technological implementation (e.g., additives to ruminant feed). We also explore the potential GHG benefits of partial (50%) or complete (100%) adoption of all five strategies simultaneously. Other combinations of strategies and their levels of adoption are provided in the Supplementary Data. We note that while we discuss food system transitions at the global scale, the magnitude and direction of the transitions will vary by country.

We find that cumulative food system GHG emissions from 2020 to 2100 can be reduced by 14–48% by changes in dietary composition and healthier caloric consumption, by increased crop yields, by decreased food loss and waste, or by increased emissions efficiency of food production, if adopted individually and gradually such that they are fully adopted in 2050 (Fig. 1). If all five strategies were to be partially implemented together (50% adoption of each), cumulative emissions to 2100 could be reduced by 63% relative to business-as-usual. Full adoption of all five strategies could result in a food system with marginally negative net cumulative emissions because of lowered emissions and net carbon sequestration on abandoned croplands (Fig. 1).

GHG emissions from all human activities impact global climate. As such, to meet a given emissions limit, there is a tradeoff between food and non-food emissions within a total cumulative budget: higher emissions from the global food system necessitate lower emissions from other sectors, and vice versa. To illustrate how emissions from all human activities might be kept under the emissions limits, we consider them within the context of an increasingly decarbonized future in which all non-food emissions and all food-related emissions from fossil fuel combustion decline linearly from current levels to zero by 2050 (*4*). This rate of reduction is approximately in line with the rates of decarbonization estimated to be needed to meet the 1.5°C target in global integrated assessment models (*16*). We find that in this increasingly decarbonized future, total global emissions from all sources (business-as-usual food + non-food) would exceed the 1.5°C limit within 11 years, and exceed the 2°C limit before the end of the century (Fig. 2a).

Assuming this linear reduction to decarbonization in 2050, meeting the 2°C target is plausible using numerous food system strategies, if also adopted by 2050 (Fig. 2a). As is well known, dietary changes, such as the adoption of plant-rich diets, can greatly reduce emissions (*5*, *6*, *17*). Even in the absence of dietary changes, achieving either high yields, high agricultural efficiency, or reducing food waste 50% alone could also meet the 2°C limit, as could partial achievement of various strategies (Fig. 2a).

Meeting the 1.5°C target with this linear decarbonization by 2050 requires at least partial achievement of multiple food system strategies: none of the five individual strategies alone are sufficient. If full implementation of these food and non-food emission changes were to be delayed by 25 years to 2075, then even 100% adoption of all five strategies would preclude meeting the 1.5°C target (Fig. 2b). For this case of slower implementation, the 2°C target could be met only by at least a 50% adoption of all five strategies, and not by any single strategy (Fig. 2b). This is because a slower adoption of food system strategies, a slower reduction of fossil fuel use in the food system, and a slower reduction in non-food emissions each necessitates larger changes to the food system to meet targets.

The need for rapid reduction in GHG emissions from fossil fuels to meet the 1.5°C or 2°C targets is widely acknowledged. We show that the same is true for food systems: even if fossil fuel emissions were rapidly reduced, emissions from the global food system are on a trajectory that would prevent achievement of the 1.5°C and 2°C targets before the end of the century. Our analyses also suggest there are many opportunities to meet the 1.5°C or 2°C emission targets. Previous analyses have suggested that global food system emissions might increase by up to 80% from 2010 to 2050 (*5*, *6*, *17*). Our findings, consistent with these results (see Supplementary Materials), improve upon these forecasts by explicitly linking food systems to IPCC cumulative emissions limits (*13*), using a novel reporting method to include CH_4 within this framework(*14*), increasing the breadth of scenarios analyzed, allowing for different levels and different rates at which food system transitions occur, providing annual emissions estimates, and forecasting beyond 2050 to 2100.

We show that meeting the 1.5°C and 2°C targets could require extensive and unprecedented changes to the global food system. Recent studies have provided insight into plausibly achievable ways to reduce food system GHG emissions. Large-scale field trials in China and the United States have shown that changes in farm management could reduce nitrogen fertilizer use and its associated GHG emissions while increasing farmer profits (*18*, *19*). Rapid increases in crop yields that decrease land clearing and its emissions have been achieved through access to improved seeds and fertilizers (*20*), and might also be achieved through the adoption of agroecological production practices, including cover crops, integrated pest management, and increased use of precision agriculture (*21*, *22*), but will require different management interventions in different regions (*23*). Food awareness, reformulation, and labeling; changes in the food environment; and education and awareness campaigns have shifted consumer food purchases in numerous countries (*24*, *25*), while carbon taxation might also be effective (*26*). Food loss and waste could be reduced by improvements to infrastructure such as grain storage and refrigeration, or by innovative methods to sell food that would otherwise be wasted (*9*). Food systems changes that reduce GHG emissions may offer additional benefits (*27*), including progress toward targets set in the Sustainable Development Goals (*28*), such as decreased nutrient pollution (*6*), reduced water pollution and scarcity (*6*), decreased land-use change (*5*, *6*, *17*), improved biodiversity outcomes (*29*), and, if dietary composition and caloric consumption are improved, reduced prevalence of obesity, diabetes, heart disease and premature mortality (*30*).

Time is of the essence in addressing GHG emissions. Any delays will necessitate more ambitious and expeditious implementation of emissions reduction strategies if global temperature targets are to be met. We show that there are many opportunities to keep emissions from food systems and other activities within the global emissions limits for the 1.5°C and 2°C targets. The global challenge of finding and implementing feasible, ethical, and equitable policies to reduce net GHG emissions will require rapid adoption of coordinated solutions within and outside of the food system that are tailored to the needs and customs of countries and the communities within them.

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Supplementary Materials:

Materials and Methods

Supplementary Text

References (*31-60*)

Fig. 1. Projected cumulative 2020 to 2100 GHG emissions solely from the global food system for business as usual and various food system changes that lead to emission reductions. Food system changes are gradually adopted between 2020 and 2050. Bars are colored by type of change to the food system: black indicates business-as-usual emissions, green indicates changes to dietary patterns, blue indicates changes to food supply chains, and gray bars indicate combined changes within all five individual strategies. The “Plant-rich diet” is based on Eat-Lancet recommendations (*15*), “Healthy calorie” Scenario contains ~2,100 daily kilocalories per person, “High yields” are 50% above current maximum potential yields, “Half waste” has food loss and waste reduced by 50%, and “High efficiency” indicates a 40% reduction in GHG emissions per unit of food produced. “50% All” and “100% All” indicate a global transition halfway (“50% All”) or entirely (“100% All”) to adoption by 2050 of Plant-rich diet, Healthy calories, High yields, Half waste, and High efficiency changes. Horizontal lines indicate maximum cumulative emissions from all sources (food and non-food) compatible with a 50% or 67% likelihood of achieving the 2°C (red) and 1.5°C (orange) temperature targets.

Fig. 2. Estimated GHG emissions from all human activities (food + non-food) for different food system changes and different rates of emissions reductions from fossil fuels and food systems. Non-food emissions are linearly reduced to zero from **(a)** 2020 to 2050 or **(b)** 2020 to 2075. Solid curves show cumulative emissions from all human activities if different food system strategies were to be implemented. Fossil fuel emissions from within the food system are also assumed to be reduced at the same rate as for emissions from outside the food system. Horizontal dashed lines indicate maximum cumulative emissions from all sources (food and non-food) compatible with a 50% or 67% likelihood of meeting the remaining 2°C (red) and 1.5°C (orange) temperature targets.

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Supplementary Materials for

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Correspondence to: michael.clark@ndph.ox.ac.uk

This PDF file includes:

Materials and Methods

Forecasting future food demand

We estimate future food demand using historic relationships between per capita food demand and per capita Gross Domestic Product ("GDP") at Purchasing Power Parity ("PPP") (*5*, *31*). We aggregate countries into 11 economic groups based on their per capita GDP in 2010 (*29*, *32*). We then estimate the global historical relationship between annual rate of increase in per capita GDP and per capita GDP using a Kuznets-like curve. We estimate per capita GDP PPP to 2100 using this empirical relationship (*31*). We then examine the historic global relationships between food demand and per capita GDP using a Gompertz 4-Parameter relationship, with different models for demand for total calories, demand for meat + fish, and demand for milk + eggs. Using these relationships, we forecast per capita food demand to 2100 for total calories, meat + fish, and milk + eggs to 2100. We calculate demand for plant-based foods as demand for total calories – (demand for meat + fish + demand for milk + eggs). We further assume that the composition of foods within each food group remains constant to 2100 (e.g., if beef consumption accounts for 25% of calories from current meat + fish consumption, then beef consumption will also account for 25% of calories from future meat + fish consumption).

Description of business-as-usual 2100 scenario

We estimate the baseline dietary demand annually from 2010 to 2100 using the aforementioned relationships between per capita GDP PPP and per capita food demand as in Tilman and Clark (2014) (*5*). Further, we assume that food loss and waste remains constant within each region for each food group (*9*), that food production efficiency remains constant; that crop yields increase along linear historic trajectories, but assuming that future crop yields does not surpass current estimated maximum potential yields (*33*); and that population increases along the United Nation's medium fertility forecasts. In the business-as-usual scenario, we further assume that composition of individual foods (e.g., rice and wheat) within each of the food groups (e.g., plants, meat + fish, and dairy + eggs) remains constant within each country through time. By pairing this assumption with our food demand projections for the different food groups, which project how much of the different food groups will be consumed in the future, we estimate future per capita demand for individual foods (e.g., beef and poultry). By pairing this with rates of food loss and waste, we estimate how much of the different foods and food groups needs to be produced to meet future demand. See below for further explanation, in addition to Tilman and Clark (2014) (*5*) and Tilman et al. (2017) (*29*).

Calculating annual food system emissions in the business-as-usual scenario

We estimate global food system emissions from food production and agricultural land-cover change. For food production, we use mean estimates of the emissions per calorie of food produced from recent life cycle analysis (LCA) meta-analyses (*8*, *10*, *34*) paired with projected dietary patterns and estimates of food loss and waste throughout the food supply chain. The LCA estimates used in our analysis include emissions from production of agricultural inputs (e.g., fertilizer) and from activities that occur during food production itself (e.g., application of fertilizer), but do not include emissions from food transportation, processing, packaging, retailing, and consumption. However, these sources of emissions are, on average, minor contributors to life cycle emissions of food systems (*10*, *35*). We make the conservative assumption that rates of food loss and waste remain constant over time, while rates of food loss and waste might in fact be increasing (*36*).

While we use GHG estimates from LCA meta-analyses with near-global coverage, we acknowledge variability and uncertainty around these mean LCA estimates. For example, the GHG emissions of producing a given food can vary depending on how and where that food is produced (*10*). However, these LCA datasets remain the best available, and our estimates of annual food system emissions are similar to those from previous analyses (see below).

To calculate GWP* (see methods below), we separated emissions by gas (specifically, it was necessary to separate methane (CH_4) from carbon dioxide (CO_2) and nitrous oxide (N_2O). Enteric fermentation and CH_4 from rice production are CH_4 emissions, and we assume that fossil fuel energy use is emitted as CO_2. For manure management, we assume a 50% share (by GWP100 CO_2e) of CH_4 and N_2O, corresponding to the global average proportion of manure emissions from CH_4 and N_2O for all livestock types and systems as reported from FAO GLEAM (*37*). While this overlooks variation in the ratio of CH_4 : N_2O emissions from manure management between different animals, locations and system types, manure emissions are rarely reported as separate species in LCA studies or reviews. As such, we did not make further assumptions over the ratio of CH_4 : N_2O from manure emissions (e.g., potential changes over time). Given the importance of separating out CH_4 emissions, we acknowledge that this represents a limitation to our approach, and call for studies to publish emissions as separate gases in the future to facilitate the use of alternative metrics and climate models (*38*).

To estimate food system land-cover change, we first estimated the amount of cropland needed to produce global food and feed demand. To do this, we calculated food + feed demand in two steps. First, global demand for plant source foods was calculated as per capita demand for plant source foods (e.g., total demand – demand for meat + fish – demand for dairy + eggs) multiplied by global population size. Second, we calculated per capita demand for feed by our estimated demand for each animal source food multiplied by food-specific feed conversion ratios (*5*). For feed demand for ruminants (e.g., beef, goat, sheep, and dairy) within each country, we assume that current productivity on pasture lands—calculated as the difference between reported feed use in FAO and estimated feed requirements based on production estimates in FAO and feed conversion ratios (*5*, *39*)—remains constant in the future, and subtracted current productivity on pasture land from estimated feed demand for ruminants. For demand for feed for fish, we assume that current global fisheries catch remains constant at 2010 levels, and that any additional demand for fish is met through feed-based aquaculture systems due to limited ability to increase fish production from wild-caught fisheries (*40*, *41*). Total per capita food + feed demand is therefore the sum of per capita demand for plant source foods + (per capita demand for ruminant feed – productivity on pasturelands) + per capita demand for feed from fish + eggs + poultry. Total country food + feed demand is per capita food + feed demand multiplied by the country's population size, and global food + feed demand is the sum of country-level food + feed demand. We do not explicitly account for crop residues used as livestock feed but do account for production on pastures as previously discussed. We note that using crop residues as livestock feed could reduce future demand for cropland and thus GHG emissions resulting from agricultural land-cover change (*42*). This assumption does not affect the other emissions categories, and has little effect on our overall conclusions because land-cover change is estimated to account for a small proportion (9%) of cumulative food system emissions in our business-as-usual scenario.

We next projected crop yields by assuming that crop yields increase along linear historic trajectories (*5*, *29*), but that future crop yields could not surpass current estimated maximum potential yields (*33*). Using this approach, we project that average global crop yields increase by 30% by 2050 and by 68% by 2100.

We then calculated global cropland use using our estimates of global food + feed demand and our estimates of crop yields, where global cropland = (global food + feed) / crop yields. Using this methodology, we estimate that there were 1.28 billion hectares of cropland used for food production in 2010, similar to the area reported by the FAO that was used for food production on cropland in 2010 (*39*). We estimate global cropland area to increase by 440 million hectares by 2050 to 1.73 billion hectares. This increase is within the range of previous estimates (*31*, *43*). We then calculated annual land-use change using our annual estimates of global cropland area from 2010 to 2100. For transparency and simplicity, we treat cropland as a single global resource even though cropland expansion and abandonment occur at national and subnational patterns. Despite this, our forecast of future cropland use and emissions from agricultural land-cover change are very similar to those in recent analyses (see below).

We then calculated annual land-cover change emissions. To do so, we first obtained spatial estimates of carbon stores in living biomass and soil (*11*, *12*). We then obtained estimates of the spatial patterns of land clearing over the previous decade from NASA satellite data (*44*). To estimate average food system land-use change emissions per hectare of cropland expansion over the previous decade, we overlaid the spatial patterns of food system cropland use expansion from the previous decade with the carbon maps. Using this methodology, we estimate that the average CO_2 emissions per hectare of food system cropland use expansion is 333 tonnes CO_2, assuming that 40% of soil organic carbon stores from the top 30 cm of soil are emitted following conversion to cropland. All GHG emissions from land-cover change are allocated to the year of agricultural expansion.

To estimate the carbon sequestration potential of average food system cropland abandonment, we overlaid spatial patterns of food system cropland use abandonment from the past decade with the carbon maps. Using this methodology, we estimate that average potential CO_2 sequestration per hectare of cropland abandonment is 211 tonnes CO_2. As with emissions from agricultural expansion, all potential carbon sequestration is allocated to the year in which agricultural land is abandoned. Using this method, we estimate that food system land-use change emissions from 2006 to 2010 averaged 4.0 Gt CO_2e per year, which is similar to the 3.78 Gt CO_2 per year of food system land-use change emissions reported in Vermeulen et al. (2012) (*2*).

To avoid overestimating GHG emission from land-cover change in cases where cropland expansion occurs after previous decreases in cropland demand (e.g., if yields increase rapidly from 2020 to 2050 and then stagnate), we assume that agricultural expansion first occurs on lands previously abandoned from agriculture, and that GHG emissions from cropland expansion on these previously abandoned lands are equivalent in magnitude to the sequestration that occurs when cropland is abandoned. In other words, there are net zero emissions on cropland if it is first abandoned and then reconverted back into agriculture. Land-use change emissions are assumed to be entirely CO_2.

For both GWP100 and GWP*, total food system emissions were then calculated as the sum of food system production emissions and food system land-use change emissions, while cumulative emissions are the sum of annual food system emissions from 2020 to 2100.

Description of the food system strategies

We estimate how different food system strategies might reduce global food system emissions. The strategies we examined are: dietary transitions; changes in caloric consumption; changes in future crop yields increases; reductions in food waste; increases in food production efficiency (reductions in emissions per unit of food produced); and the pace at which food system changes are achieved (linear increase in adoption through complete adoption of the changes in either 2050 or 2075). We estimate food system production and land-use change emissions from these scenarios using the same methodology as described for the business-as-usual scenario. Results for all combinations of these food system strategies at different levels and rates of adoption are available in the Supplementary Data, and the data inputs and code required to run the analyses are available for download as a Supplementary Material.

Rate at which food system strategies are implemented

For each food system change, we assume linear adoption from 2020 until the adoption year (2050 or 2075), at which point the food system change is entirely adopted. We assume that the composition of diets (e.g., the proportion of calories from plants or beef), caloric consumption, crop yields, food waste, and production efficiency remain constant after the adoption year. The population scenarios are independent of adoption year (i.e., global annual population in the low fertility pathway is identical in each year regardless of adoption year), while the amount of calories consumed only converges at the adoption year if the calorie scenario is not the business-as-usual caloric trajectory.

Dietary patterns

We examined a plant-rich diet that is equivalent to the Eat-Lancet diet and contains a moderate amount of meat and fish each week (*15*). In the plant-rich diet strategy (i.e., non business-as-usual dietary trajectory), diets are assumed to linearly approach from the business-as-usual dietary pattern to the plant-rich diet based on the proportion of each food type consumed in the two diets. Dietary composition within major food groups (e.g., meat or plants) also changes in the plant-rich diet strategy to converge to recommended intakes as estimated in the EAT-Lancet Commission (*15*).

Caloric intake

The business-as-usual food system assumes that per capita caloric intake increases along historic associations between per capita caloric intake and per capita GDP PPP. We consider a “healthy calories” strategy where caloric intake reduces to an amount that would maintain an average body mass index (BMI of ~22.5) at current average activity levels (~2,085 calories per capita per day) (*30*). This caloric intake was estimated based on population demographics and physical activity rates, which are known to be determinants of caloric requirements as noted in ref 24 and elsewhere (*36*).

The business-as-usual caloric trajectory is not altered by the adoption year. As such, the total caloric intake in the business-as-usual caloric scenarios is equivalent when adoption year is 2050 or 2075. Similarly, for the adoption year of 2050 or 2075, caloric intake follows business-as-usual trajectories until 2050 or 2075 independent of adoption year and remains constant thereafter. In this strategy, caloric intake linear converges from current intake to 2,085 calories per capita per day at the adoption year. We assume that healthy caloric intake remains at 2,085 calories, but acknowledge that a healthy caloric intake may increase or decrease if the global population experiences large changes in demographics and activity levels (*30*, *36*).

Crop yields increases

The business-as-usual food system assumes that crop yields increase along historic linear trajectories, but that crop yields cannot surpass current estimated maximum potential yields (*33*). As a result, we project that business-as-usual crop yields will increase 30% from 2010 to 2050 and 68% from 2010 to 2100 as discussed above.

In addition to the business-as-usual yield trends, we examined one alternative crop yield strategy: that crop yields increase to 150% of current maximum potential yields (*33*). While this alternative yield strategy is ambitious, bioengineering of photosynthetic pathways in tobacco plants has been shown to increase yields by nearly 40% in field trials (*45*). Such technologies may make achievement of the alternative yield strategies possible if widely implemented.

In food system scenarios with a convergence year of 2050 or 2075, we assume that yields linearly increase from current yields in 2020 to the maximum yield (either the business-as-usual yields or 50% above current potential yields, depending on the yield strategy in the food system scenario) by the adoption year (2050 or 2075) and then remain constant thereafter.

Food Waste

We examined two projections of food loss and waste: the business-as-usual rates of food loss and waste, and the strategy where food loss and waste is reduced by 50%. For business-as-usual, we assume that food loss and waste throughout the entire supply chain is equivalent to what is estimated by the FAO (*9*). FAO estimates of food loss and waste vary by food type (e.g., there are separate estimates for meat, dairy, and seafood) and by region. In the strategy where food loss and waste is reduced by 50%, we assume that food loss and waste is reduced throughout the entire food supply chain for each food type by 50%. Due to our assumption that food loss and waste remains constant in the business-as-usual scenario, we likely provide conservative estimates of food system GHG emissions because recent evidence indicates that rates of food loss and waste throughout food supply chains might be increasing (*36*).

For food system scenarios with adoption year of 2050 or 2075, food loss and waste through the entire supply chain declines linearly to such that 50% reduction is achieved in the stated adoption year, at which point no further change in food loss and waste occurs until 2100.

Food production efficiency

The business-as-usual food system assumes that food production efficiency, or GHG emissions per unit of food produced, remains constant at current levels. The alternative strategy we examined is that GHG emissions of each GHG species (i.e., CO_2, N_2O, and CH_4) per unit of food produced are decreased by 40%. This reduction is applied to all sources of emissions from food production, and is assumed to occur linearly from 2020 until the adoption year (2050 or 2075).

Intensity of food system strategies

For each of the five types of food system strategies described above (dietary patterns, caloric intake, crop yield increases, food loss and waste, and food production efficiency), we examined two rates of implementation: partial 50% adoption and complete 100% adoption. Note that, as above, the changes are assumed to occur gradually from 2020 to the adoption year, such that the transitions are only fully realized in the adoption year.

For dietary composition, the set endpoint was global adoption of a plant-rich diet. As such, a 50% deviation from current business-as-usual trajectories is equivalent to half of the world adopting a plant-rich diet (or everyone transitions halfway to a plant-rich diet from current business-as-usual trajectories).

For caloric content, the set endpoint was global adoption of healthy caloric intake. As such, a 50% deviation from current business-as-usual trajectories to healthy caloric intake means that the projected difference between future caloric intake and healthy caloric intake is gradually reduced by half.

For crop yields, the set endpoint was for future crop yields to be 50% above current maximum potential yields. As such, a 50% deviation from current business-as-usual crop yields to the most ambitious crop yields examined means that the difference between projected future crop yields and 50% above current maximum potential yields is reduced in half.

For food loss and waste, the set endpoint was a 50% reduction in food loss and waste. As such, a 50% deviation from current business-as-usual food loss and waste means that food loss and waste gradually decreases from current levels to 25% (half of 50%) lower than current levels.

For food production efficiency, the set endpoint was a 40% reduction in GHG emissions per unit of food produced. As such, a 50% deviation from current production efficiency to the most ambitious increase in production efficiency examined means that GHG emissions per unit of food produced would decrease by 20% (half of 40%).

Results from every possible combination of these food system strategies are available in the Supplement Data. Other food system strategies are available to run in the scripts found in the Supplementary Materials. See the Read Me file for the scripts for more information on these strategies.

Cumulative emissions budgets

Cumulative emission budgets to keep warming to 1.5–2°C above pre-industrial levels

Because the temperature impact of CO_2 emissions at a given point in time is an approximately linear function of emissions to date, cumulative CO_2 emissions budgets can be used to define total allowable CO_2 emissions that are compatible with a given temperature target (*46*). This observation forms the basis of the emissions budgets reported in the IPCC Special Report on Global Warming of 1.5°C (SR15). The 'headline' budgets communicated by the report are CO_2

only budgets that express the total CO_2 emissions that can be released, after a deduction from the permissible temperature ceiling based on assumed emission pathways of non-CO_2 gases (*1*, *47*). As a significant proportion (the majority, under the GWP100 CO_2 equivalence metric) of agricultural emissions are CH_4 and N_2O emissions rather than CO_2, these budgets are not directly applicable to agricultural GHG emissions. Instead, following the same logic behind the approach in SR15, we work directly from the TCRE (transient climate response to cumulative carbon emissions), using the emissions budgets provided in table 2.SM.1 of the report's supplementary materials to chapter 2 (*13*), which represent CO_2 budgets for various levels of additional warming before making any deductions for non-CO_2 gases. Current temperatures are approximately 1°C above pre-industrial levels (*47*), and so we use the CO_2 budgets from this table representing a further 0.5°C or 1.0°C warming. We use the 67th percentile of the normally distributed ranges of the TCRE to err on the side of caution, resulting in global emissions budgets of 615 and 1,520 Gt CO_2e for total warming of 1.5°C and 2°C above pre-industrial temperatures, respectively. To acknowledge uncertainty in these estimates, we also include the emissions limits estimated to result in a 50% of meeting the 1.5°C and 2°C targets in Figures 1 and 2, which were also derived from table 2.SM.1 of the IPCCs SR15 (*13*). These emissions limits are 820 and 1,931 Gt CO_2e, respectively.

GWP - an application of Global Warming Potentials to include short-lived greenhouse gases in a 'CO_2 warming-equivalent' emissions budget framework*

The most commonly employed GHG emission metric, the 100-year Global Warming Potential (GWP100), can misrepresent short-lived greenhouse gas emissions in some situations (including cumulative emission budgets), as their impacts are largely non-cumulative. To overcome this, we use an alternative application of Global Warming Potentials, GWP*, to express CH_4 emissions as 'CO_2 warming-equivalents' compatible with a cumulative emissions budget approach (*14*). A proportion of CO_2 emissions persist in the atmosphere for millennia, and so ongoing emissions will cumulatively add to atmospheric concentrations (*48*). Other long-lived gases such as N_2O (with an atmospheric lifetime of approximately 121 years (*49*)) will act similarly, with emissions acting cumulatively over policy-relevant timescales shorter than the lifespan of the gas (*50*). For short-lived gases such as CH_4 (atmospheric lifetime of approximately 12 years (*49*)), any emissions will undergo chemical change to other species over a period of decades following release, and therefore ongoing emissions will not act cumulatively. As such, CH_4 emissions will not exhaust a cumulative emissions budget in the same manner as emissions of long-lived gases such as CO_2 and N_2O. This fundamental difference between the cumulative and non-cumulative behaviors of long- and short-lived gases would not be captured if we use GWP100 CO_2 equivalents as conventionally applied, and so would not be compatible with cumulative emissions budget approaches (and was not designed with this purpose in mind). Instead, GWP* treats changes in the rate of emissions of short-lived gases such as CH_4 as equivalent to a one-off release of CO_2 (*14*, *50–52*), defined (in annualized form) as:

$$E_{\mathrm{CO_2we}} = \mathrm{GWP}_{100} \times \left[75 \times \frac{\Delta E_{\mathrm{CH4}}}{20} + 0.25 \times E_{\mathrm{CH4}}\right] \qquad \text{(eqn. 1)}$$

Where $E_{\mathrm{CO_2we}}$ denotes a CO_2-warming-equivalent emission, $\Delta E_{(CH_4)}$ the change in the rate of CH_4 emissions over the preceding 20 years, $E_{(CH_4)}$ the emissions of CH_4 in a given year, and GWP_{100} the 100-year Global-Warming-Potential of CH_4 (for this study we use GWP values from the IPCC 5th Assessment Report) (*14*, *53*).

Thus, under GWP*, stable CH_4 emission rates contribute only a relatively small CO_2-we (warming equivalent) emission, reflecting that under constant emission rates an equilibrium will be reached where atmospheric concentrations of the gas are maintained by the ongoing emissions rate. Increasing CH_4 emission rates are reflected as a large CO_2-we emission, and can exceed the GWP100 of CH_4 if rates increase at more than approx. 1% per year (*54*). Declining CH_4 emission rates are reported as a *negative* CO_2-we emission, as if CH_4 emissions are not sustained at current rates atmospheric concentrations will fall and a portion of the warming they had caused will be undone – having an equivalent effect to active CO_2 removal.

For our total CO_2-we budgets, CO_2 emissions are added directly, and N_2O emissions follow conventional usage of GWP100:

$$E_{CO_2we} = E \times GWP_{100} \qquad \text{(eqn. 2)}$$

GWP* has been argued as a straightforward but informative approach of incorporating CH_4 in a cumulative emissions budget approach (*14*), as recommended in the IPCC SR 1.5 (*55*).

Estimating GHG emissions from outside the food system

To include emissions from outside food systems within the context of cumulative emissions limits and temperature targets, we estimated cumulative GHG emissions from non-food system activities.

To calculate cumulative GHG emissions from non-food system activities, we use reported global emissions in 2012 from PRIMAP-hist database as our baseline (*4*). Because 2012 emissions were the last year where all sources of GHG emissions were reported in PRIMAP, we assume that 2012 emissions remained constant through to 2020.

To forecast future non-food system GHG emissions, we assume that GHG emissions from activities outside of the food system linearly decline from current rates (e.g., 2012—the most recently reported—estimates as reported in PRIMAP) in 2020 to zero by either 2050 or 2075. While this is a straightforward assumptions of emissions from outside food systems, these rates of reductions in non-food GHG emissions are approximately similar to the faster (2050) and slower (2075) rates of reductions in fossil fuel use that have been estimated to be needed to meet the 1.5°C target (*16*). However, we assume that current annual rates of CH_4 emissions from landfills, waste treatment, and biomass burning (~75.6Pg CH_4, or ~30% of current anthropogenic CH_4 emissions) remain constant through time (*56*). We then estimated cumulative GWP* emissions using the methodology described above. As a result, our estimates of GHG emissions from activities outside the food system are 369 Gt CO_2-we assuming non-food system emissions decrease to zero in 2050, and 837 Gt CO_2-we assuming that non-food system emissions decrease to zero in 2075.

Estimating GHG emissions in 2018 and 2019

Because our analysis forecasts cumulative GHG emissions from 2020 to 2100 but the emissions limits start in 2018, we next estimated GHG emissions in 2018 and 2019.

We calculated GHG emissions in 2018 and 2019 in two parts. First, we calculated emissions from non-food system activities. To do so, we estimated GWP* emissions from CH_4, N_2O, and CO_2 as described in the previous section. The total sum of these emissions is estimated to be 83

Gt CO_2-we. Second, we estimated GHG emissions from activities within the food system based on our forecast of dietary patterns in 2018 and 2019 using the methodology described in the section "Calculating annual food system emissions in the business-as-usual scenario". It was necessary to use forecasted food system estimates in 2018 and 2019 because the most recent year of data in the FAO's Food Balance Sheets was 2013 at the time the paper was submitted. Using the methodology, we estimate that food system emissions in 2018 and 2019 sum to 34 Gt CO_2-we. As such, total global GHG emissions from all activities in 2018 and 2019 are estimated to be 117 Gt CO_2-we.

This means that after accounting for GHG emissions in 2018 and 2019, the remaining emissions limits to have a 67% chance of meeting the 1.5°C and 2°C targets are 500 and 1,405 Gt CO_2-we, respectively. For a 50% chance of meeting the targets, the emissions limits are 705 and 1,816 Gt CO_2-we, respectively.

Supplementary Text

Comparison of the business-as-usual scenario to other projections

Our estimates of future increases in total food production and per capita food demand are similar to existing estimates, with differences in methodologies of forecasting per capita and global food demand as described below.

Future total food + feed production

For total food production from 2010 to 2050, we estimate a 75% increase in total calories from food+feed production, which is in the range of recent estimates (*57*). For instance, Alexandratos and Bruinsma (2012) (*43*) projected a 60% increase 2005/7 to 2050; Tilman et al (2011) (*31*) projected a 110% increase from 2005 to 2050; and IMPACT, a global partial equilibrium model developed by IFPRI, projects an 88% increase by mass from 2010 to 2050 (*58*).

Future per capita food demand

Our estimates are also similar to existing forecasts when examined on a per capita food demand basis (*57*). For total calories, we estimate that per capita caloric demand, measured as the calories available for food consumption, will increase by 15% between 2010 and 2050 (from 2,890 calories per capita in 2010 to 3,320 calories in 2050), compared to 11% (from 2,772 calories per capita per day in 2005/7 to 3,070 calories per day in 2050) in Alexandratos and Bruinsma (2012) (*43*), 15% (from 2,800 calories per capita to day in 2010 to 3,210 in 2050) in IMPACT (*58*). In addition, our estimate is within the range of forecasted 2050 daily per capita caloric demand reported in Bodirsky et al. (2015), which range from 3,177 – 3,566 calories per person per day (*59*), and also follows the broad trajectories described in Pradhan et al. (2013) (*60*).

Future cropland area

We next calculate future annual cropland demand by first estimating total global production using our estimates of global caloric demand, livestock specific feed conversion ratios, current production on pasturelands and rangelands. We then divide the estimated total global production with our crop yield forecasts, which we estimate to increase by 68% from 2010 to 2100. Doing this shows that our estimates of future cropland use and cropland expansion are also within the range of existing estimates of cropland expansion (*5*, *31*, *57*). Using this approach, we project that there will be 440 million hectares of cropland expansion from 2010 to 2050, increasing from 1.28 billion hectares in 2010 to 1.73 billion hectares in 2050. Tilman et al. (2011) project an increase of ~1 billion hectares over 2005 to 2050, Tilman and Clark (2014) estimate an average increase of 540 million hectares from 2010 to 2050. Our estimates of cropland expansion are slightly higher than those predicted in global assessment models (*57*), largely because the assessment models assume faster-than-historic increases in future crop yields whereas our yield forecasts assume that crop yields increase along historic trajectories.

Current emissions from food systems

We compared our estimates of annual GHG emissions from food systems (using GWP100, not GWP*) in 2010 to validate our methodology against recent estimates of GHG emissions from food systems (*2*, *3*, *27*). Using our methodology, we estimate the annual food system GHG emissions from food production (excluding land-use change) averaged 9.25 Gt CO_2e per year from 2010 to 2020. This is within the range of recent estimates (*2*, *3*, *27*). Combining this estimate with our estimated GHG emissions from food system land-use change from 2006 to 2010 (4.0 Gt CO_2 per year), we estimate that food system emissions in 2010 were approximately 13.3 Gt CO_2e per year. This estimate is within the range of recent estimates of emissions from food systems and food-related land-use change, including those reported in Vermeulen et al. (2012) (estimated range of 9.2–15.0 Gt CO_2e per year) (*2*), the recent IPCC report on Climate Change and Land (estimated range of 10.8–19.1 Gt CO_2e per year) (*27*), and Rosenzweig et al (2020) (estimated range of 10.8–19.1 Gt CO_2e per year) (*3*).

Future emissions from food systems

We also compared our estimates of food system GHG emissions in 2050 (again, using GWP100) to estimates in previous analyses. We estimate the food system GHG emissions in 2050 will be 16.5 Gt CO_2 per year, with 14.6 Gt CO_2 per year from production and 1.9 Gt CO_2 per year from food-related land-cover change. Thus, we estimate that annual emissions from food production are likely to increase by nearly 60% from 2010 to 2050. Our estimated 60% increase in global annual food production emissions is within the range of previous estimates (*5*, *6*, *15*, *17*, *58*).

Comparison to Shared Socioeconomic Pathways (SSPs) and Integrated Assessment Models (IAMs)

For non-food system emissions, we consider a simple scenario of how emissions might rapidly reduce over time, rather than directly modelling the economic factors or technologies that enable these emission reductions, as in IAMs. However, due to the physical constraints in what must be achieved to stay under 1.5°C or 2°C, our pathways are not greatly dissimilar to those generated under ambitious IAMs (see also the simple framing of emission pathways in the IPCC SR1.5).

For food system emissions, we construct a food system modeling framework to adjust each food system strategy (dietary composition, caloric consumption, crop yields, food loss and waste, and production intensity) to explicitly analyze the GHG benefit of each of these strategies. In contrast, IAMs typically bundle sets of economic, behavioral and technological assumptions regarding the development of the food system into a smaller number of model runs, which can complicate identifying the role of specific interventions. We provide the results of a large number (123) of projections so that users can explore our data, including identifying combinations that align with specific IAM scenarios.