CLIMATE CHANGE

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

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

The goal of the Paris Agreement is to limit average global temperature increases above preindustrial levels to "well below 2°C" and to pursue efforts to "limit increase to 1.5°C." Achieving either goal requires large and rapid 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, and 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° 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 these emissions 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 the 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 billion tonnes (Gt) CO_2 equivalents year^{-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° 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, which we refer to as business-as-usual (*5*, *6*). This business-as-usual forecast makes straightforward assumptions: (i) per capita dietary composition and caloric consumption continue to change as countries become more affluent (*5*); (ii) crop yields, which influence how much land is converted to cropland, increase along recent trajectories (*5*); (iii) global population increases along the United Nation's medium-fertility pathway (*7*); and (iv) 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 largely occur from food production and from land being 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 these estimates 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 Intergovernmental Panel on Climate Change (IPCC) Tier 1 estimates of GHG emissions from land clearing or carbon storage in biomass and soil after land abandonment (*11*, *12*).

We next determine the maximum allowable cumulative GHG emissions from all human activities from 2020 onward that are compatible with having a 67 or 50% chance of meeting the 1.5° and 2°C targets, on the basis of the thresholds set in the IPCC Special Report on Global Warming of 1.5°C (*13*). We call these the emissions limits. To accurately incorporate CH_4 into the cumulative emissions framework, we report emissions as global warming potential (GWP*) CO_2 warming-equivalents (CO_2-we) (*14*). We also show results with the more commonly used GWP100 (100-year GWP) metric in data S2. To have a 67% chance of meeting the 1.5° and 2°C targets, the cumulative emissions limits are 500 and 1405 Gt CO_2-we, respectively. For a 50% chance of meeting the targets, the emissions limits are 705 and 1816 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° or 2°C target. Our estimate of cumulative business-as-usual food system emissions from 2020 to 2100 is 1356 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 nonfood emissions to <50 Gt CO_2-we in total over the next 80 years. This is slightly more than 1 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 nonfood emissions, which is 9 years of current nonfood emissions (*4*). These general trends hold even if emissions from fossil fuel use in the global food system were also to be 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: (i) globally adopting a plant-rich diet [here modeled as a diet rich in plant-based foods that contains moderate amounts of dairy, eggs,

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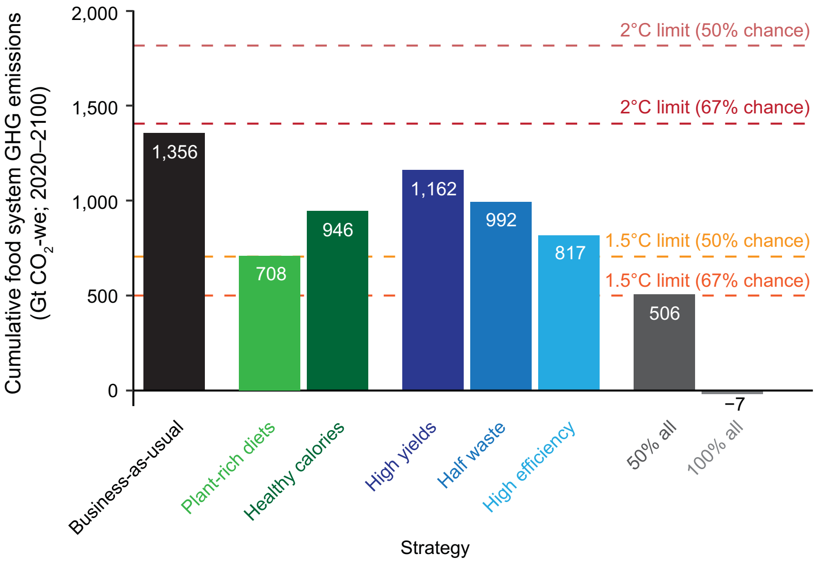

Fig. 1. Projected cumulative 2020 to 2100 GHG emissions solely from the global food system for business-as-usual emissions and for various food system changes that lead to emission reductions. Food system changes are gradually adopted between 2020 and 2050. Bars are colored by type of change to the food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

and meat, such as a Mediterranean diet or planetary health diet (*15*)]; (ii) adjusting global per capita caloric consumption to healthy levels; (iii) achieving high yields by closing yield gaps and improving crop genetics and agronomic practices; (iv) reducing food loss and waste by 50%; and (v) 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 data S2. Although 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 to 48% through changes in dietary composition and healthier caloric consumption, through increased crop yields, through decreased food loss and waste, or through increased emissions efficiency of food production, provided that these strategies are adopted individually and gradually such that they are fully adopted by 2050 (Fig. 1). If all five strategies were to be partially implemented together (50% adoption of each), cumulative emissions through 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 affect global climate. As such, to meet a given emissions limit, there is a tradeoff between food and nonfood 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 in the context of an increasingly decarbonized future in which all nonfood 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 plus nonfood) would exceed the 1.5°C limit within 11 years, and they would 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 through the use of numerous food system strategies, provided that they are 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 a 50% reduction in food waste 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 nonfood 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 nonfood 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° 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° and 2°C targets before the end of the century. Our analyses also suggest there are many opportunities to meet the 1.5° 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 on these forecasts by explicitly linking food systems to IPCC cumulative emissions limits (*13*), using a reporting method to include CH_4 in 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° and 2°C targets will likely require extensive and unprecedented changes to the global food system.

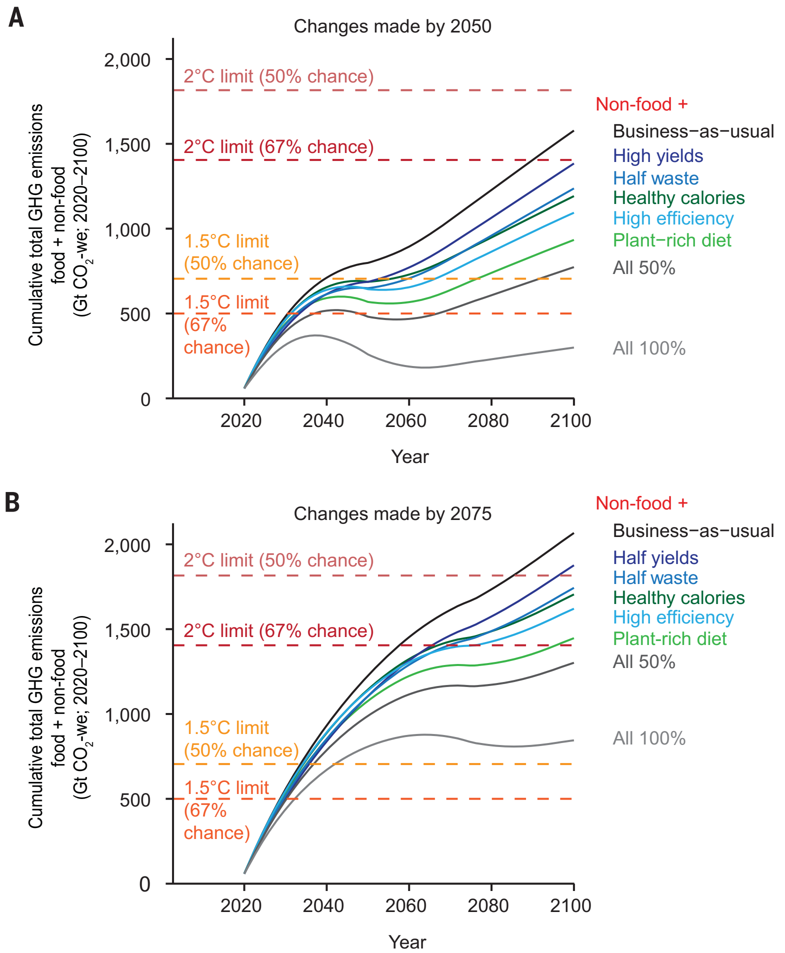

Fig. 2. Estimated GHG emissions from all human activities (food plus nonfood) for different food system changes and different rates of emissions reductions from fossil fuels and food systems. (**A** and **B**) Nonfood emissions are linearly reduced to zero from 2020 to 2050 (A) or from 2020 to 2075 (B). 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 nonfood) compatible with a 50 or 67% likelihood of meeting the remaining 2° (red) and 1.5°C (orange) temperature targets.

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*). Such increases in yields 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*). 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 system changes that reduce GHG emissions may offer additional benefits (*27*), including progress toward targets set in the United Nations' 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° and 2°C targets. The global challenge of finding and implementing feasible, ethical, and equitable policies to reduce net GHG emissions will require the rapid adoption of coordinated solutions, both within and outside of the food system, that are tailored to the needs and customs of different countries and the communities within them.

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ACKNOWLEDGMENTS

We are grateful to M. Springmann, C. Godfray, P. Scarborough, and K. Kimmel, who provided comments on the manuscript. **Funding:** This research was made possible through funding from the Balzan Award Prize to D.T.; the Grand Challenges Research Initiative at the University of Minnesota; the Wellcome Trust, Our Planet Our Health (Livestock, Environment and People), award no. 205212/Z/16/Z; and the U.S. Department of Agriculture (MIN-12-083). This publication was also developed as part of the Center for Air, Climate, and Energy Solutions, which was supported under Assistance Agreement no. R835873 awarded by the U.S. Environmental Protection Agency (EPA). It has not been formally reviewed by the EPA. The views expressed in this document are solely those of the authors and do not necessarily reflect those of the EPA. The EPA does not endorse any products or commercial services mentioned in this publication. **Author contributions:** J.D.H., N.G.G.D., K.C., S.K.T., D.T., M.A.C., and J.L. conceptualized the project; M.A.C., J.D.H., D.T., N.G.G.D., and J.L. developed the project methodology; M.A.C., N.G.G.D., D.T., and J.D.H. performed the analysis; M.A.C., J.D.H., and D.T. visualized the results; M.A.C. wrote the original draft; and all authors contributed to the review and editing of the manuscript. **Competing interests:** The authors declare no competing interests. **Data and materials availability:** Data used to create the figures is available in data S1. Results from all analyses are available in data S2. All data inputs and code required to run the analyses are available for download as data S3.

SUPPLEMENTARY MATERIALS

science.sciencemag.org/content/370/6517/705/suppl/DC1
Materials and Methods
Supplementary Text
References (*31–60*)
Data S1 to S3

8 January 2020; accepted 1 September 2020
10.1126/science.aba7357

Science

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

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Science **370** (6517), 705-708.
DOI: 10.1126/science.aba7357

Thought for food

To have any hope of meeting the central goal of the Paris Agreement, which is to limit global warming to 2°C or less, our carbon emissions must be reduced considerably, including those coming from agriculture. Clark *et al.* show that even if fossil fuel emissions were eliminated immediately, emissions from the global food system alone would make it impossible to limit warming to 1.5°C and difficult even to realize the 2°C target. Thus, major changes in how food is produced are needed if we want to meet the goals of the Paris Agreement.

Science, this issue p. 705