Climate change and the urgency to transform food systems

Monika Zurek [1], Aniek Hebinck [2], Odirilwe Selomane [3]

[1] Food Systems Transformation Group, Environmental Change Institute, University of Oxford, UK
[2] Dutch Research Institute for Transitions (DRIFT), Erasmus University Rotterdam, NL
[3] Centre for Sustainability Transitions, Stellenbosch University, SA

Abstract

Without rapid changes to agriculture and food systems the goals of the 2015 Paris Agreement on climate change will not be met. Food systems are one of the most important contributors to greenhouse gas (GHG) emissions, but they also need to further adapt to climate change impacts. Although many options exist to reduce GHG emissions in the food system, efforts to develop implementable transformation pathways are hampered by a combination of structural challenges such as fragmented decision making, vested interests, and power imbalances in the climate policy and food communities, all compounded by a lack of joint vision. New processes and governance arrangements are urgently needed for dealing with potential trade-offs among mitigation options and their food security implications.

Climate change poses one of the greatest threats to human societies, demanding immediate and coordinated actions across all sectors (*1*). Food systems are one of the most important contributors to climate change (*2*), and could compromise efforts to achieve the 2015 Paris Agreement targets (*3*). At the same time, food systems themselves will also need to further adapt to climate change impacts. The latest IPCC report shows that climate change has already negatively impacted food production across the world and contributed to malnutrition (*4*). Temperature rises beyond 1.5°C are expected to transform terrestrial land ecosystems and shift climate-zones (*5*), pressuring food security and livelihoods by affecting the productivity of crops and livestock (*4*), while warming of the oceans will reduce productivity of fisheries and aquaculture (*6*). Together with more extreme weather events and sea level rise, this level of temperature increase will exacerbate inequities in food access as food prices are likely to increase too (*7*).

Simultaneously, food systems are responsible for about a third of the global anthropogenic greenhouse gas (GHG) emissions (*2*), presenting a major challenge (and opportunity) for climate change mitigation (*8*). There are three significant pathways through which the food system contributes to GHG emissions and that present entry points transformative change. The first pathway is through crop and livestock production, including all the activities required to ensure raw products leave the farm. These activities generate GHG emissions mainly through methane and nitrous oxide emissions largely from enteric fermentation by domestic ruminants (cows, sheep, and goats) and their manure, fertilizer applications on crops, and methane production from flooded rice fields (*9*, *10*). Together, crops and livestock systems currently contribute 10 - 14% of total GHG emissions, which could increase up to 40 percent of emissions by 2050 under some scenarios (*7*, *9*). The second major pathway is land-use change, which contributes to GHG emissions mainly through deforestation and destruction of peatlands for agricultural purposes. Agriculture related land use emissions are estimated to be between 5 – 14 percent of total emissions (*7*, *9*). The third pathway is through food related activities beyond the farmgate, ranging from food processing and transport to food consumption. Food system related emissions beyond the farmgate are estimated at 5 – 10 percent of total emissions (*9*).

Coordinated and successful implementation of a 'menu' of mitigation and adaptation options for agriculture and food systems on a global scale is suggested to reduce GHG emissions to a safe level and support transformation to sustainable food systems (*10*). Mitigation options in the food system are generally organised around four key areas, which include improvements in the management of crops and livestock, land use change, and food value chains, as well as by altering food consumption patterns (including reducing food waste). While agricultural activities and land use change are leading to a higher proportion of food system emissions than post farm gate activities it needs to be noted that consumer dietary choices are a substantial factor for driving decisions made on farm. That said, post farm emissions (e.g. from energy use in food processing, food transport, food storage, cooking) have been rising substantially in recent years, requiring a rethink of mitigation strategies for the food sector (*11*). A look across the whole food system therefore becomes important for finding the biggest levers of change.

Designing a menu of mitigation (and adaptation) measures

While mitigation and adaptation options are plentiful in the food system (*12*), their implementation remains fragmented and uncoordinated, risking trade-offs with other food system outcomes such a food security or livelihood outcomes (*13*, *14*). Harnessing the climate change mitigation and adaptation potential in food systems will require a critical system perspective (*15*) to understand pros and cons of these options, as well as relations among different actors that might impact the implementation of an intervention. This approach could also help to look beyond mitigation and adaptation options that target agriculture - which until now has been a dominant focus in literature and practice (*8*) - to better include other activities down the food chain. For this, the diverse and interrelated activities that make up the food chain, as well as the wider social-ecological context and driving forces it is situated in, need to be considered (*15*). A food system approach (**Figure 1**) can illuminate several intervention points along the chain by modifying the drivers of food system activities (*16*). For example, farm activities can either contribute to GHG emissions, or sequester carbon, depending on production practices (*17*). Similarly, dietary choices at the household level can result in significant gains in reducing meat-related emissions (*18*).

That said, transformation of food systems around the globe is urgent, not only because of their GHG emissions but also because they fall completely short in equitably distributing food and providing food and nutrition security (*19*), resulting in hunger, malnutrition, and overconsumption (*20*). In addition, their wider environmental footprint related to biodiversity loss, deforestation, soil degradation and water pollution is a key driver of environmental degradation (*21*). As currently organized, the food system also falls short on providing equal economic opportunities to food system actors and social equity outcomes (*15*, *22*) (see **Figure 1**).

Here we review key food system climate change mitigation options and take a systems perspective to explore interactions with the main food system outcomes. We then examine some of the key stumbling blocks to achieving necessary mitigation efforts in food systems and point to new ideas for overcoming these to bring about tangible food system change with mitigation benefits.

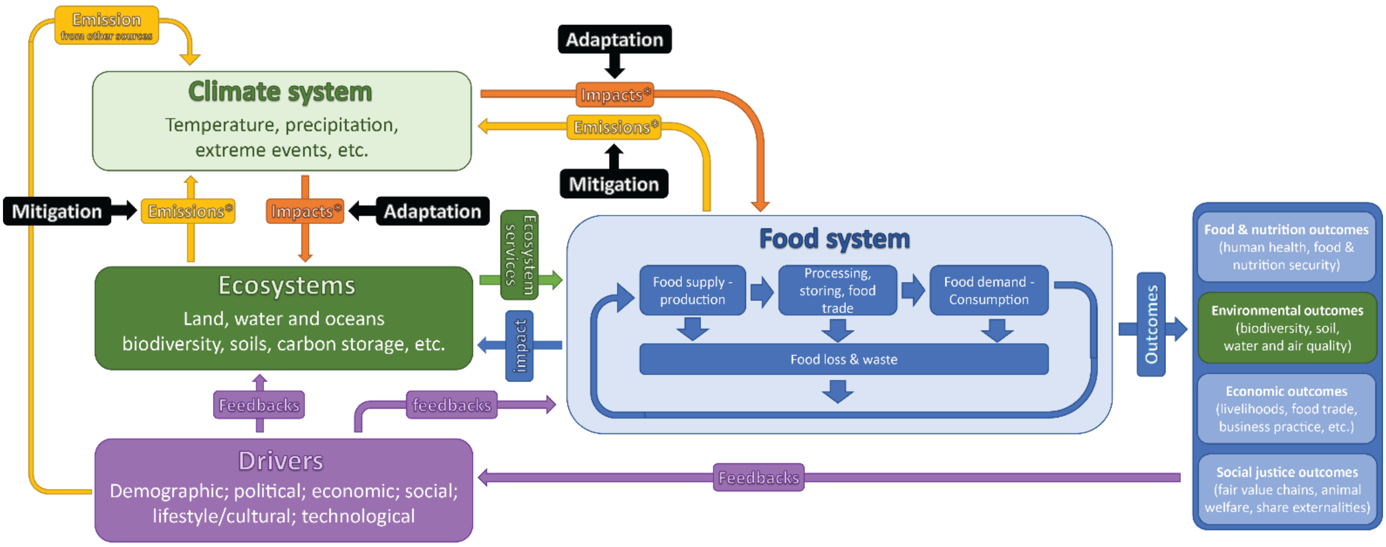

Figure 1. A food system perspective of climate change interactions with the food system: a two way street

Climate change mitigation options in food systems

Climate change mitigation strategies across the entire food system fall into four main categories. We review some of the most important options, which range from improvements to cropping systems, livestock production, and supply chain activities, as well as changing demand for products high in GHG emissions (Table 1). While all these options have GHG emission reduction benefits they also have implications for other food system outcomes by creating potential synergies and trade-offs. Table 1 presents a few illustrations of these interactions, which need to be analysed in their specific contexts to be able to assess their benefits.

Fostering synergies can offer a multitude of co-benefits. For example, agroforestry practices have major benefits not only for the environment by fixating nitrogen, and enhancing soil carbon sequestration, but also benefit society by increasing crop productivity by enhancing soil nutrients and organic matter. However, the adoption of agroforestry practices is often complicated by obstacles specific to the farming system context, such as managing the risk of an unsuccessful transition (e.g. lack of safety nets in case new practices don't work), needing different inputs or new knowledge to change practices.

Adoption of a mitigation measure can nevertheless be complicated by associated trade-offs with food system outcomes. For example, closing yield gaps (i.e., the difference between the potential yield for a particular crop under optimal conditions and average farmers' yields in a particular location) has a significant role to play in climate mitigation through reduction of demand for new land. However, closing the yield gap requires resource inputs, such as water and fertiliser (*23*), which might not be locally available and their use could have other, possibly negative, environmental impacts (*24*). Similarly, strategies for reducing GHG emissions from enteric fermentation in ruminants, which produces methane and is the biggest contributor to food related GHG emissions, by for example incorporating seagrass into cattle feed has a large mitigation potential, but large scale seagrass harvesting will likely result in negative effects on marine ecosystems and also reduce their carbon sequestration potential (30).

While options for mitigating climate change in agriculture and the wider food system exist, it is still not clear how these can be combined to achieve the needed GHG emissions reductions to contribute best to the targets of the Paris Agreement. Wollenberg *et al.* (*41*) were the first to calculate a potential target for agricultural emissions reductions by 2030 so that the sector could contribute sufficiently to the 2°C goal of the Paris Agreement. The authors then analysed if this target could be reached using various currently available agricultural mitigation technologies (for examples see Table 1) and concluded they would only deliver 21 – 40 percent of the needed GHG emission reductions. Far reaching efforts to develop further transformational technological and policy options are essential if agriculture and food systems are to play the significant role they should in achieving the Paris Agreement goals.

Table 1. Climate change mitigation strategies across the food system

Mitigation Areas	Food systems responses	Examples of potential interactions with other food system outcomes (food and nutrition security, economic, environmental, and social)
Improved crop management	*Reducing nitrous oxide emissions synthetic fertiliser applications*	Synthetic fertiliser applications are critical to the food system, especially as often manure and legumes can only provide a portion of total nitrogen demands of crop production. They have contributed to substantial gains in productivity of food crops and will continue to be important going forward, as demand for food is expected to increase. But overapplication of fertilizer have led to major environmental impacts (*21*).
	Reducing methane emissions from paddy rice	Implementation of new agricultural management practices (e.g. Alternative Wetting and Drying) to the many (small holder) farmers globally requires massive inputs from extension services (*25*), which brings uncertainties about the effectiveness of implementation.
	Improving land use management for carbon sequestration [and reducing its losses]	The potential of carbon sequestration in agricultural lands is debated though it could be (with global variations) considered a co-benefit of improving cropland and grazing land management (*26*). Restoration of peatlands and the reforestation of marginal and unimprovable agricultural lands should be a priority, but conflicts with the increased demand for food (*27*).
	Closing yield gaps (differences between yields under optimal conditions and those attainable in farmers' fields)	Yield gaps have a significant role to play in reducing land needed for food. Improving yield gaps relies primarily on nutrients (fertiliser) and water management (*23*). In some areas, water required to close the yield gap might not be locally available (*24*). In terms of nutrients, some areas, and regions of the world such as Sub-Saharan Africa will need to increase their fertiliser use (*28*), and this will further increase the GHG emissions, while many other parts of the world need to reduce fertilizer overapplication.
	Agroforestry	Agroforestry is a land sharing strategy that accommodates both agricultural production with biodiversity protection, resulting in improved nitrogen fixation, land and ecosystem health, and soil carbon sequestration, among other benefits. However, the implementation of this strategy depends on landowners and managers on the ground to accept and adopt these practices and faces various socio-economic barriers to adoption. Based on lessons from challenges related to conservation agriculture (*29*), agroforestry is facing the similar challenges of low adoption. To be successful, it will require investment on the ground to facilitate uptake, in a way that is beneficial to landowners and managers.
Improved livestock management	*Better grazing land management*	
	Improved manure management	
	Higher quality feed	There are various new options for reducing methane emissions via new changed feeding practices for ruminants. For example, Roque et al. (*30*) suggested that introducing seaweed into the diets of cattle can reduce their methane emissions by up to 80% through changing the bacterial conditions in their guts. But upscaling seaweed harvesting would have large scale implications for marine ecosystems, including their carbon sequestration potential.
	Reduction of enteric fermentation	Two main strategies for reducing enteric fermentation include feed additives and improving feed digestibility. Feed additives, while beneficial, have also been highlighted to have negative human health (*31*) and environmental impacts. Given the increasing health and other risks of antibiotic and pesticide resistance, feed additives are not a clear strategy for mitigation without their negative impacts (*32*).

	Reduce nitrous oxide through manure management	
	Sequestering carbon in pastures	
	Implementing best animal husbandry and management practices	
Integrated approaches to crop and livestock	*Decoupling livestock from land use*	Consumption of animal protein is likely to continue and grow into the future and will likely compete for land with human food through feed demand (*33*).
	Non-animal protein sources	
	Microbial protein as feedstuff	
Improved supply chain	*Improved food transport and distribution*	Mitigation options here take two general forms. In low- and middle-income countries where storage and processing facilities may be lacking, mitigation is geared towards reducing food loss through innovations and technology (e.g., cool storage options at the last mile) (*34*). In upper middle- and high-income countries where use of technology and infrastructure is widespread, mitigation is geared towards improving energy use efficiency, and transitioning towards renewable energy sources (*8*). A potential trade-off with the food system outcomes depends on the type of renewable energy sources used - the discussion about the potential impacts of biofuels, when not done right, on food security is well documented (*35*).
	Improved efficiency and sustainability of food processing, retail and agrifood industries	
	Improved energy efficiencies of agriculture	
	Reduction of food loss	A large share of the total produced food is never consumed and is lost in the pre- or postconsumption stage. Reducing the amount of food loss would allow for a smaller yield to meet the global food demand, resulting in reduced emissions related to food production. Mitigation measures to address this often come in the form of innovations to improve the efficiency of food harvesting and processing. To reach the middle and smallholder farmers that have little to no access to such facilities, these innovations need to be both accessible and affordable (*10*, *34*).
Demand management	*Dietary changes towards sustainable consumption and healthy diets*	Reduction in meat (especially beef and lamb) consumption is expected to have the biggest outcome for climate change and the environment (*9*, *33*), especially as general food demand and meat in specific are projected to increase. Many current dietary choices have negative impacts on environmental sustainability and health (*36*). The growing number of upper and middle-income consumers on average over-consume food, contributing to an increased food demand, GHG emissions, and food waste (*33*). Switching to healthy diets and following food guidelines has the potential to improve environmental sustainability (including mitigation of climate change), and improvement in health outcomes (*37*, *38*). However, these diets have also been found to be unaffordable and not accessible to the majority of the world's poor and marginalised (*39*).
	Reduce food waste	The Food Waste Index report estimates that nearly a billion tonnes of food was wasted in 2019. Over 60% of this waste was due to household's level waste, with food service and retail respectively contributing 26% and 13% (*40*). Reducing food waste has multiple co-benefits and provides synergistic outcomes for both people (e.g., improving food security, regulating prices) and planet (e.g., reducing pressure on land, biodiversity, and climate change).
	Transparency of food chains and external costs	

What are systemic challenges to reducing food-related emissions?

Despite scientific validation of possible mitigation options and strategies for addressing climate change, society has collectively failed to implement options or to 'bend the curve' towards lower emissions. Several systemic and power-related issues, such as lack of coordinated climate action and vested interests in fossil fuel industries, are in part to blame. But also, unbalanced power relations within food systems hinder progress in adoption of mitigation strategies (*42*, *43*). Besides obstructing the lowering of emissions, these issues have also exacerbated inequities between high and middle-and-low-income countries, as climate impacts have thus far mostly impacted the latter (*20*). Stoddard *et al.* (*42*) set out the structural issues that have prevented any 'bending of the curve', and in this section we will also explore how these structural issues result in trade-offs between equity and climate change mitigation in food systems.

Addressing climate change is to a large extent a political matter, which involves negotiations between governments and other stakeholders about how to coordinate action on a global scale (*44*). By coordinating and giving shape to climate action, the so-called 'climate change regime' (*42*, *45*, *46*) has provided the dominant structure for such negotiations. It is this dominant governance arrangement that also decides about the allocation of responsibility for mitigation of climate change between states, amidst North-South geopolitics (*44*). However, this is not an equal playing field and concerns have been raised about how powerful countries have undue influence on the process. Furthermore, hindering coordinated action in this governance arrangement are the lack of binding targets for emissions, requirements for technology transfer, and funding for low-income countries (*42*) These issues directly influence food-related mitigation strategies in low-and-middle income countries that are most vulnerable to climate impacts (*13*). In addition, the consensus-based decision-making approach might block the approval of mitigation options that benefit low-middle income countries, but that disadvantage high income countries (*42*).

Although global climate governance has developed targets for the reduction of fossil fuel use and GHG emissions at a national level, wealthy countries nevertheless often outsource their environmental footprint and GHG emissions to other, poorer countries while also using land elsewhere for carbon offsetting at the expense of the people who live there (*47*, *48*). In addition, vested interests from fossil fuel and dependent industries intervene on the decision-making processes at national level (*42*), often pushing for non-transformative solutions that include technological optimism (*49*). Influence from such vested interests tends to lead to the adoption of the least disruptive changes often leaning on future technological breakthroughs that ultimately justify business as usual (*49*, *50*). Similarly, in the debate on the role of food systems in climate change mitigation, more narrow technological solutions have received much attention, often overlooking unintended or hidden social justice consequences (*51*, *52*), for example, when innovative solutions are inaccessible to vulnerable food system actors, thus further widening the gap between rich and poor (*13*). In addition, the focus on tech-based solutions has side lined debate on the role of alternative, innovative solutions that are more place-based and scale appropriate for small scale farmers, such as agroecology (*50*). The financial sector has also played an important role in shaping today's food economy by financing fossil-fuel reliant industries and business practices and that have now become a vital part of their business model. Large-scale conventional agricultural practices are made possible by private-sector finance and investments (*53*). By investing in responses and solutions that are preferred from a financial perspective, financial actors have been influential in determining how climate risks are managed by food system actors, for example by proposing various carbon trading mechanisms (*54*). However, because of the close relation between fossil fuel dependence and economic growth, scholars are concerned about the feasibility of combining the current growth paradigm with the successful implementation of mitigation options (*55*). Scholars call for more transformative and just climate governance, which calls for the 'polluter elite' and transnational companies to take responsibility (*43*). In this scenario, financial capital institutions should develop and implement more innovative finance mechanisms to support more transformative food system practices (*56*).

While justice has been a core motivation for governing climate change at a global level, it is primarily understood in terms of equitable responsibility for climate change or just responses to climate change. This notion assumes that nation-states can protect and enforce climate justice, which overlooks the multiple dimensions of justice associated with climate change and narrows down action to north-south or developed-developing divides (*43*). This interpretation has obstructed the implementation of more transformative mitigation options. First, the focus on the nation-state has overlooked the role of private sector actors – such as the food industry – in climate mitigation. While innovation of alternative and more sustainable practices and products is considered key for climate mitigation, decreased public spending has left their development primarily in the hands of private actors who often pursue for-profit aims rather than the common good (*13*). Second, much of the debate on climate mitigation is viewed from a global scale, somewhat disconnected from the local level and what consequences mitigation measures might have on small communities and individuals (*57*, *58*). Not ignoring potential incompatibility between the mostly globally defined mitigation options and the locally oriented adaptation measures, arguing that even if a mix could be found it would be extremely difficult to implement (*59*).

Interlocking decisions

Food systems, and in particular their agricultural production activities, which are often driven by consumer food choices, are both a major source of global GHG emissions while also requiring concerted efforts to adapt agriculture and all other food system activities to new temperature regimes, precipitation patterns or extreme events in the future. Thus, policy and decision makers are faced with three interlocking decisions when looking for how to mitigate climate change in food systems: 1) The mitigation options that are available to them in their specific contexts; 2) How much GHG emission reduction can be achieved by each measure or a combination of different ones and 3) How these options interact with food and nutrition security, the economic, and social outcomes of the food system, as well as with necessary climate adaptation measures? **Table 1** shows examples of the interlinkages between a range of mitigation options and food system outcomes. Reducing the amount of ruminant meat in diets for example, discussed in many countries as the main avenue for consumers to contribute to GHG emission reductions, can also help with the unwelcome negative health impacts of meat overconsumption but will impact livestock farmers' livelihoods directly by reducing demand and will also have implications for land use and landscape management and thus biodiversity.

Navigating these questions will require evidence on the pros and cons for each mitigation option within a specific food system and eventually decisions must be made that will very likely not please everyone. Due to the interconnected nature of food systems these choices will bring with them unintended and unanticipated consequences, resulting in trade-offs for some actors within the system (e.g. reducing meat consumption is likely to change livestock producers' income) and trade-offs between food system outcomes (e.g. environmental footprint versus income). Making these trade-offs better visible is important for finding ways to address them from the start. This is where a food system perspective is essential as it connects the activities of various stakeholders to food system outcomes. To change outcomes, activities need to change, which is incentivized by changing food system drivers (e.g., governance structures, institutions, tax regimes, available science and technology options).

Reforming current structures and vested interests

How decisions are taken and who takes them depends very much on the specific context of a food system and how it is governed. Many governments for example are now including agricultural mitigation options in their Nationally Determined Contributions to the Paris Agreement (NDCs), which are then meant to translate into concrete incentives for farmers and/or food industry actors to implement mitigation actions. What input these actors have when the decisions are taken depends on the institutional mechanisms available within their respective country contexts. While many technical options are becoming available for both adaptation and mitigation in different food system contexts it has not been straightforward to translate them into tangible changes on the ground. And even more difficult is balancing these options with the main task of food systems - to provide food and nutrition security, while also providing livelihoods and economic opportunities, managing wider ecosystem outcomes, and making food systems more equitable. This is where understanding vested interests on the one side and the current structures governing both climate change policy making, as well as the food system becomes important, especially if we want to reach a just transition of our economy and our food systems that takes the needs for the vulnerable groups into consideration.

Although food systems differ so much across the world in their components and contexts, we will nevertheless need to develop clear transformation pathways, so they can play their part in achieving the Paris Agreement goals. How to decide on the right mix of mitigation and adaptation options within the specific food system would benefit from developing positive visions specifying what mix of food system outcomes actors want and what trade-offs between them they are willing to make. This requires some form of negotiation between actors, acknowledging winners and losers of different options for change, to provide coordinated innovation pathways and trade-off management. Several steps could be helpful for this:

- Map the food system in question with its dynamics and actors/activities, involving the relevant stakeholders, while assessing its current outcomes to create a joint understanding of food system process and boundaries (for an example of a food system map see (*60*)). For this a set of compatible, integrated food system outcome metrics is also needed (9). Ideally, this should be done at the scale at which decisions on mitigation actions are taken (e.g. the national level for the NDCs).
- Using participatory foresight methods, such as scenario planning or visioning, and based on the food system map, develop food system scenarios to explore the implications and trade-offs of possible mitigation (and adaptation) options. Here it is particularly important to engage multiple stakeholders across the food system and include vulnerable groups and actors that might be negatively affected by possible change options.
- Based on the scenario analysis, determine coordinated, systemic mitigation innovation pathways (including various change options) with a view of the whole system.
- Translate the mitigation innovation pathways into tailored actions for different food system actors, such as producers, value chain actors, consumers, or policy makers. This needs to include actions to reduce or deal with trade-offs/unintended consequences.
- Evaluate and monitor food system outcomes based on selected food system metrics to determine if and how well the implemented mitigation innovation pathways work.
- Adjust actions as needed based on the monitoring results.

Conclusion

The capacity to develop options for mitigating climate change in agriculture and food systems is available. What is nevertheless difficult to achieve is deciding on the set of options that need to work together in a specific food system to achieve multiple goals that societies care about and implement these in a consistent manner. For this we need to acknowledge and work with power imbalances, vested interest and fragmented policy making and monitor outcomes to learn and adjust.

Food system change cannot wait, and neither can action on climate change mitigation, in which the food system has an ever more important part to play.

References

1. C. Rosenzweig, C. Mbow, L. G. Barioni, T. G. Benton, M. Herrero, M. Krishnapillai, E. T. Liwenga, P. Pradhan, M. G. Rivera-Ferre, T. Sapkota, F. N. Tubiello, Y. Xu, E. Mencos Contreras, J. Portugal-Pereira, Climate change responses benefit from a global food system approach. *Nature Food*. **1**, 94–97 (2020).

2. M. Crippa, E. Solazzo, D. Guizzardi, F. N. Tubiello, A. Leip, Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food* (2021), doi:10.1038/s43016-021-00225-9.

3. M. A. Clark, N. G. G. Domingo, C. Kimberly, S. K. Thakrar, T. David, L. John, I. L. Azevedo, J. D. Hill, Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. *Science (1979)*. **370**, 705–708 (2020).

4. IPCC, in *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, H.-O. Pörtner, D. C. Roberts, E. S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, Eds. (Cambridge University Press. In Press., 2022). https://www.ipcc.ch/report/ar6/wg2/

5. W. Wang, A. Pijl, P. Tarolli, Future climate-zone shifts are threatening steep-slope agriculture. *Nature Food*. **3**, 193–196 (2022).

6. H. E. Froehlich, R. R. Gentry, B. S. Halpern, Global change in marine aquaculture production potential under climate change. *Nature Ecology & Evolution*. **2**, 1745–1750 (2018).

7. FAO, *The future of food and agriculture – Alternative pathways to 2050* (2018; http://www.fao.org/3/I8429EN/i8429en.pdf).

8. M. T. Niles, R. Ahuja, T. Barker, J. Esquivel, S. Gutterman, M. C. Heller, N. Mango, D. Portner, R. Raimond, C. Tirado, S. Vermeulen, Climate change mitigation beyond agriculture: a review of food system opportunities and implications. *Renewable Agriculture and Food Systems*. **33**, 297–308 (2018).

9. C. Mbow, C. Rosenzweig, L. G. Barioni, T. G. Benton, M. Herrero, M. Krishnapillai, E. Liwenga, P. Pradhan, M. G. Rivera-Ferre, T. Sapkota, F. N. Tubiello, Y. Xu, “Food Security” (2019). In : IPCC Special Report - Climate Change and Land: Chapter 5 - Food Security. https://www.ipcc.ch/srccl/

10. WRI, “Creating a sustainable food future: A menu of solutions to feed nearly 10 billion people by 2050” (Washington D.C, 2018).

11. F. N. Tubiello, K. Karl, A. Flammini, J. Gütschow, G. Obli-Laryea, G. Conchedda, X. Pan, S. Y. Qi, H. Halldórudóttir Heiðarsdóttir, N. Wanner, R. Quadrelli, L. Rocha Souza, P. Benoit, M. Hayek, D. Sandalow, E. Mencos Contreras, C. Rosenzweig, J. Rosero Moncayo, P. Conforti, M. Torero, Pre- and post-production processes increasingly dominate greenhouse gas emissions from agri-food systems. *Earth System Science Data*. **14**, 1795–1809 (2022).

12. A. M. Loboguerrero, B. M. Campbell, P. J. M. Cooper, J. W. Hansen, T. Rosenstock, E. Wollenberg, Food and Earth Systems: Priorities for Climate Change Adaptation and Mitigation for Agriculture and Food Systems. *Sustainability* . **11** (2019), , doi:10.3390/su11051372.

13. M. Zurek, A. Hebinck, O. Selomane, Looking across diverse food system futures: Implications for climate change and the environment. *Q Open*. **1**, 1–39 (2021).

14. I. D. Brouwer, J. McDermott, R. Ruben, Food systems everywhere: Improving relevance in practice. *Global Food Security*. **26**, 100398 (2020).

15. A. Hebinck, M. Zurek, T. Achterbosch, B. Forkman, A. Kuijsten, M. Kuiper, B. Nørrung, P. van 't Veer, A. Leip, A Sustainability Compass for policy navigation to sustainable food systems. *Global Food Security*. **29**, 100546 (2021).

16. J. Ingram, *Food System models*, in Lawrence, M, Friel, S. Healthy and Sustainable Food Systems. Routledge, London. 2019. https://doi.org/10.4324/9781351189033

17. S. J. Vermeulen, B. M. Campbell, J. S. I. Ingram, Climate Change and Food Systems. *Annual Review of Environment and Resources*. **37**, 195–222 (2012).

18. J. Poore, T. Nemecek, Reducing food's environmental impacts through producers and consumers. *Science (1979)*. **360**, 987–992 (2018).

19. E. Holt-Giménez, A. Shattuck, M. Altieri, H. Herren, S. Gliessman, We Already Grow Enough Food for 10 Billion People … and Still Can't End Hunger. *Journal of Sustainable Agriculture*. **36**, 595–598 (2012).

20. FAO, IFAD, UNICEF, WFP, WHO, "The State of Food Security and Nutrition in the World 2021. Transforming food systems for food security, improved nutrition and affordable healthy diets for all" (Rome, 2021), doi:https://doi.org/10.4060/cb4474en.

21. B. M. Campbell, D. J. Beare, E. M. Bennett, J. M. Hall-Spencer, J. S. I. Ingram, F. Jaramillo, R. Ortiz, N. Ramankutty, J. A. Sayer, D. Shindell, Agriculture production as a major driver of the earth system exceeding planetary boundaries. *Ecology and Society*. **22** (2017), doi:10.5751/ES-09595-220408.

22. S. Whitfield, M. Apgar, C. Chabvuta, A. Challinor, K. Deering, A. Dougill, A. Gulzar, F. Kalaba, C. Lamanna, D. Manyonga, L. O. Naess, C. H. Quinn, T. S. Rosentock, S. M. Sallu, K. Schreckenberg, H. E. Smith, R. Smith, P. Steward, K. Vincent, A framework for examining justice in food system transformations research. *Nature Food* (2021), doi:10.1038/s43016-021-00304-x.

23. N. D. Mueller, J. S. Gerber, M. Johnston, D. K. Ray, N. Ramankutty, J. A. Foley, Closing yield gaps through nutrient and water management. *Nature*. **490**, 254–257 (2012).

24. K. F. Davis, M. C. Rulli, F. Garrassino, D. Chiarelli, A. Seveso, P. D'Odorico, Water limits to closing yield gaps. *Advances in Water Resources*. **99**, 67–75 (2017).

25. Z. Cui, H. Zhang, X. Chen, C. Zhang, W. Ma, C. Huang, W. Zhang, G. Mi, Y. Miao, X. Li, Q. Gao, J. Yang, Z. Wang, Y. Ye, S. Guo, J. Lu, J. Huang, S. Lv, Y. Sun, Y. Liu, X. Peng, J. Ren, S. Li, X. Deng, X. Shi, Q. Zhang, Z. Yang, L. Tang, C. Wei, L. Jia, J. Zhang, M. He, Y. Tong, Q. Tang, X. Zhong, Z. Liu, N. Cao, C. Kou, H. Ying, Y. Yin, X. Jiao, Q. Zhang, M. Fan, R. Jiang, F. Zhang, Z. Dou, Pursuing sustainable productivity with millions of smallholder farmers. *Nature*. **555**, 363–366 (2018).

26. M. Lessmann, G. H. Ros, M. D. Young, W. de Vries, Global variation in soil carbon sequestration potential through improved cropland management. *Global Change Biology*. **28**, 1162–1177 (2022).

27. B. W. J. Freeman, C. D. Evans, S. Musarika, R. Morrison, T. R. Newman, S. E. Page, G. F. S. Wiggs, N. G. A. Bell, D. Styles, Y. Wen, D. R. Chadwick, D. L. Jones, Responsible agriculture must adapt to the wetland character of mid-latitude peatlands. *Global Change Biology*. **n/a** (2022), doi:https://doi.org/10.1111/gcb.16152.

28. S. Leitner, D. E. Pelster, C. Werner, L. Merbold, E. M. Baggs, F. Mapanda, K. Butterbach-Bahl, Closing maize yield gaps in sub-Saharan Africa will boost soil N2O emissions. *Current Opinion in Environmental Sustainability*. **47**, 95–105 (2020).

29. B. Brown, R. Llewellyn, I. Nuberg, Global learnings to inform the local adaptation of conservation agriculture in Eastern and Southern Africa. *Global Food Security*. **17**, 213–220 (2018).

30. B. M. Roque, M. Venegas, R. D. Kinley, R. de Nys, T. L. Duarte, X. Yang, E. Kebreab, Red seaweed (Asparagopsis taxiformis) supplementation reduces enteric methane by over 80 percent in beef steers. *PLOS ONE*. **16**, e0247820 (2021).

31. Y. Hu, H. Cheng, S. Tao, J. L. Schnoor, China's Ban on Phenylarsonic Feed Additives, A Major Step toward Reducing the Human and Ecosystem Health Risk from Arsenic. *Environmental Science & Technology*. **53**, 12177–12187 (2019).

32. P. S. Jørgensen, A. Aktipis, Z. Brown, Y. Carrière, S. Downes, R. R. Dunn, G. Epstein, G. B. Frisvold, D. Hawthorne, Y. T. Gröhn, G. T. Gujar, D. Jasovský, E. Y. Klein, F. Klein, G. Lhermie, D. Mota-Sanchez, C. Omoto, M. Schlüter, H. M. Scott, D. Wernli, S. P. Carroll, L. with R. project, Antibiotic and pesticide susceptibility and the Anthropocene operating space. *Nature Sustainability*. **1**, 632–641 (2018).

33. M. B. Eisen, P. O. Brown, Rapid global phaseout of animal agriculture has the potential to stabilize greenhouse gas levels for 30 years and offset 68 percent of CO2 emissions this century. *PLOS Climate*. **1**, e0000010 (2022).

34. A. R. Hansen, C. Keenan, G. Sidhu, "Nutritious Food Foresight: Twelve ways to invest in good food in emerging markets." (2019). Global Knowledge Initiative. Funded by Global Alliance for Improved Nutrition.

35. T. Searchinger, R. Edwards, D. Mulligan, R. Heimlich, R. Plevin, Do biofuel policies seek to cut emissions by cutting food? *Science (1979)*. **347**, 1420–1422 (2015).

36. M. A. Clark, M. Springmann, J. Hill, D. Tilman, Multiple health and environmental impacts of foods. *Proc Natl Acad Sci U S A*. **116**, 23357–23362 (2019).

37. N. Wilson, C. L. Cleghorn, L. J. Cobiac, A. Mizdrak, N. Nghiem, Achieving Healthy and Sustainable Diets: A Review of the Results of Recent Mathematical Optimization Studies. *Adv Nutr*. **10**, S389–S403 (2019).

38. W. Willett, J. Rockström, B. Loken, M. Springmann, T. Lang, S. Vermeulen, T. Garnett, D. Tilman, F. Declerck, B. Crona, E. Fox, V. Bignet, M. Troell, T. Lindahl, S. Singh, S. E. Cornell, K. S. Reddy, S. Narain, S. Nishtar, C. J. L. Murray, The Lancet Commissions Food in the Anthropocene : the EAT – Lancet Commission on healthy diets from sustainable food systems. **6736** (2019), doi:10.1016/S0140-6736(18)31788-4.

39. K. Hirvonen, Y. Bai, D. Headey, W. A. Masters, Affordability of the EAT–Lancet reference diet: a global analysis. *The Lancet Global Health*. **8**, e59–e66 (2020).

40. UNEP, "Food Waste Index Report 2021" (Nairobi, 2021). https://www.unep.org/resources/report/unep-food-waste-index-report-2021

41. E. Wollenberg, M. Richards, P. Smith, P. Havlík, M. Obersteiner, F. N. Tubiello, M. Herold, P. Gerber, S. Carter, A. Reisinger, D. P. van Vuuren, A. Dickie, H. Neufeldt, B. O. Sander, R. Wassmann, R. Sommer, J. E. Amonette, A. Falcucci, M. Herrero, C. Opio, R. M. Roman-Cuesta, E. Stehfest, H. Westhoek, I. Ortiz-Monasterio, T. Sapkota, M. C. Rufino, P. K. Thornton, L. Verchot, P. C. West, J.-F. Soussana, T. Baedeker, M. Sadler, S. Vermeulen, B. M. Campbell, Reducing emissions from agriculture to meet the 2 °C target. *Global Change Biology*. **22**, 3859–3864 (2016).

42. I. Stoddard, K. Anderson, S. Capstick, W. Carton, J. Depledge, K. Facer, C. Gough, F. Hache, C. Hoolohan, M. Hultman, N. Hällström, S. Kartha, S. Klinsky, M. Kuchler, E. Lövbrand, N. Nasiritousi, P. Newell, G. P. Peters, Y. Sokona, A. Stirling, M. Stilwell, C. L. Spash, M. Williams, Three Decades of Climate Mitigation: Why Haven't We Bent the Global Emissions Curve? *Annual Review of Environment and Resources*. **46**, 653–689 (2021).

43. P. Newell, S. Srivastava, L. O. Naess, G. A. Torres Contreras, R. Price, Toward transformative climate justice: An emerging research agenda. *WIREs Climate Change*. **12**, e733 (2021).

44. R. Falkner, The Paris Agreement and the new logic of international climate politics. *International Affairs*. **92**, 1107–1125 (2016).

45. C. Okereke, P. Coventry, Climate justice and the international regime: before, during, and after Paris. *WIREs Climate Change*. **7**, 834–851 (2016).

46. D. Loorbach, in *Transformative Climate Governance: A Capacities Perspective to Systematise, Evaluate and Guide Climate Action*, K. Hölscher, N. Frantzeskaki, Eds. (Springer International Publishing, Cham, 2020; https://doi.org/10.1007/978-3-030-49040-9_13), pp. 431–445.

47. J. Fairhead, M. Leach, I. Scoones, Green Grabbing: a new appropriation of nature? *The Journal of Peasant Studies*. **39**, 237–261 (2012).

48. R. Fuchs, C. Brown, M. D. A. Rounsevell, Europe's Green Deal offshores environmental damage to other nations. *Nature*. **586**, 671–673 (2020).

49. W. F. Lamb, G. Mattioli, S. Levi, J. T. Roberts, S. Capstick, F. Creutzig, J. C. Minx, F. Müller-Hansen, T. Culhane, J. K. Steinberger, Discourses of climate delay. *Global Sustainability*. **3**, e17 (2020).

50. A. J. Nightingale, S. Eriksen, M. Taylor, T. Forsyth, M. Pelling, A. Newsham, E. Boyd, K. Brown, B. Harvey, L. Jones, R. Bezner Kerr, L. Mehta, L. O. Naess, D. Ockwell, I. Scoones, T. Tanner, S. Whitfield, Beyond Technical Fixes: climate solutions and the great derangement. *Climate and Development*. **12**, 343–352 (2020).

51. B. K. Sovacool, M. Martiskainen, A. Hook, L. Baker, Decarbonization and its discontents: a critical energy justice perspective on four low-carbon transitions. *Climatic Change*. **155**, 581–619 (2019).

52. J. J. Patterson, T. Thaler, M. Hoffmann, S. Hughes, A. Oels, E. Chu, A. Mert, D. Huitema, S. Burch, A. Jordan, Political feasibility of 1.5°C societal transformations: the role of social justice. *Current Opinion in Environmental Sustainability*. **31**, 1–9 (2018).

53. J. Clapp, Financialization, distance and global food politics. *The Journal of Peasant Studies*. **41**, 797–814 (2014).

54. P. Newell, O. Taylor, P. Newell, O. Taylor, Contested landscapes : the global political economy of climate-smart agriculture agriculture. *The Journal of Peasant Studies*. **0**, 1–22 (2017).

55. J. Hickel, G. Kallis, Is Green Growth Possible? *New Political Economy*. **25**, 469–486 (2020).

56. A. Khatri-Chhetri, T. B. Sapkota, B. O. Sander, J. Arango, K. M. Nelson, A. Wilkes, Financing climate change mitigation in agriculture: assessment of investment cases. *Environmental Research Letters*. **16**, 124044 (2021).

57. M. Hulme, (Still) Disagreeing About Climate Change : What Way Forward ? *Journal of Religion and Science* **2015**, 1–15 (2015). https://doi.org/10.1111/zygo.12212

58. J. David Tàbara, J. Jäger, D. Mangalagiu, M. Grasso, Defining transformative climate science to address high-end climate change. *Regional Environmental Change*. **19**, 807–818 (2019).

59. P. Watkiss, M. Benzie, R. J. T. Klein, The complementarity and comparability of climate change adaptation and mitigation. *WIREs Climate Change*. **6**, 541–557 (2015).

60. S. Hasnain, J. S. I. Ingram, M. Zurek, "Mapping the UK Food System - a report for the UKRI Transforming UK Food Systems Programme" (2020), doi:978-1-874370-81-9.