The EAT–*Lancet* Commission on healthy, sustainable, and just food systems

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Executive summary

The global context has shifted dramatically since publication of the first EAT–*Lancet* Commission in 2019, with increased geopolitical instability, soaring food prices, and the COVID-19 pandemic exacerbating existing vulnerabilities and creating new challenges. However, food systems remain squarely centred at the nexus of food security, human health, environmental sustainability, social justice, and the resilience of nations. Actions on food systems strongly impact the lives and wellbeing of all and are necessary to progress towards goals highlighted in the Sustainable Development Goals, the Paris Agreement, and the Kunming–Montreal Global Biodiversity Framework. Although current food systems have largely kept pace with population growth, ensuring sufficient caloric intake for many, they are the single most influential driver of planetary boundary transgression. More than half of the world's population struggles to access healthy diets, leading to devastating consequences for public health, social equity, and the environment. Although hunger has declined in some regions, recent increases linked to expanding conflicts and emergent climate change impacts have reversed this positive trend. Obesity rates continue to rise globally, and the pressure exerted by food systems on planetary boundaries shows no signs of abating. In this moment of increasing instability, food systems still offer an unprecedented opportunity to build the resilience of environmental, health, economic, and social systems, and are uniquely placed to enhance human wellbeing while also contributing to Earth-system stability.

This updated analysis builds upon the 2019 EAT–*Lancet* Commission, expanding its scope and strengthening its evidence base. The first Commission defined food group ranges for a healthy diet and identified the food systems' share of planetary boundaries. In this Commission, we add an analysis of the social foundations for a just food system, and incorporate new data and perspectives on distributive, representational, and recognitional justice, providing a global overview on equity in food systems. Substantial improvements in modelling capacity and data analysis allow for the use of a multimodel ensemble to project potential outcomes of a transition to healthy and sustainable food systems.

The planetary health diet (PHD) remains a cornerstone of our recommendations and can be seen as a framework within which diverse and culturally appropriate diets can exist. Robust updated evidence reinforces a strong association with improved health outcomes, large reductions in all-cause mortality, and a substantial decline in the incidence of major diet-related chronic diseases. The reference PHD emphasises a balanced dietary pattern that is predominantly plant-based, with moderate inclusion of animal-sourced foods and minimal consumption of added sugars, saturated fats, and salt. Successful implementation of the PHD requires careful consideration of cultural contexts and the promotion of culturally appropriate and sustainable dietary traditions. This diversity of contexts, bounded by the PHD's reference values, represents substantial flexibility and choice across cultures, geographies, and individual preferences. However, when confronted by climate, biodiversity, health, and justice crises, transformation will require urgent and meaningful changes in our individual and collective behaviours and our culture of unhealthy, unjust, and unsustainable food production and consumption.

For the first time, we quantify the global food systems' share of all nine planetary boundaries. These food system boundaries confirm that food is the single largest cause of planetary boundary transgressions, driving the transgression of five of the six breached boundaries. In addition, food systems exert a notable impact on the transgressed climate boundary and on the ocean acidification boundary. Unsustainable land conversion, particularly deforestation, remains a major driver of biodiversity loss and climate change, highlighting the need for zero conversion of all remaining intact ecosystems. Food systems account for the near totality of nitrogen and phosphorus boundary transgression, emphasising the improvements needed in nutrient management, efficient nutrient redistribution, and circular nutrient systems. The massive use of novel entities in food production, processing, and packaging (ranging from plastics to pesticides) remains a major concern but is alarmingly understudied.

Our assessment of justice integrates three dimensions—distributive, representational, and recognitional—within a

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Key messages

- Food systems sit at the nexus of health, environment, climate, and justice. A food systems transformation is fundamental for solving crises related to the climate, biodiversity, health, and justice. The central position of food systems emphasises the interdependent nature of these crises, rather than each crisis separately, which highlights the need to position food systems change as a global integrator across economic, governance, and policy domains.
- The updated planetary health diet (PHD) has an appropriate energy intake; a diversity of whole or minimally processed foods that are mostly plant sourced; fats that are primarily unsaturated, with no partially hydrogenated oils; and small amounts of added sugars and salt. The diet allows flexibility and is compatible with many foods, cultures, dietary patterns, traditions, and individual preferences. The PHD also provides nutritional adequacy and diminishes the risks of non-communicable diseases. At present, all national diets deviate substantially from the PHD, but a shift to this pattern could avert approximately 15 million deaths per year (27% of total deaths worldwide). Such a transition would reduce the rates of many specific non-communicable diseases and promote healthy longevity.
- Food drives five planetary boundary transgressions, including land system change, biosphere integrity, freshwater change, biogeochemical flows, and approximately 30% of greenhouse gas emissions driving climate change. How and where food is produced, which foods are produced and consumed, and how much is lost and wasted, all contribute to planetary boundary transgressions. No safe solution to climate and biodiversity crises is possible without a global food systems transformation. Even if a global energy transition away from fossil fuels occurs, food systems will cause the world to breach the Paris Climate agreement of limiting global mean surface temperature to 1·5°C.
- Human rights related to food systems (ie, the rights to food, a healthy environment, and decent work) are not being met, with nearly half the world's population below the social foundations for these rights. Meanwhile, responsibility for planetary boundary transgressions from food systems is not equal: the diets of the richest 30% of the global population contribute to more than 70% of the environmental pressures from food systems. Just 1% of the global population is in a safe and just space. These statistics highlight the large inequalities in the distribution of both benefits and burdens of current food systems. National policies that address inequities in the distribution of benefits and burdens of current food systems would aid in ensuring food-related human rights are met.
- The PHD needs to be available, affordable, convenient, aspirational, appealing, and delicious. To increase demand for healthy sustainable diets and enable necessary dietary shifts, food environment interventions, next-generation culinary research and development, increased purchasing power, and protection and promotion of healthy traditional diets are important actions.
- A food systems transformation following recommendations from the EAT–*Lancet* Commission—which include a shift to healthy diets, improved and increased agricultural productivity, and reduced food loss and waste—would substantially reduce environmental pressures on climate, biodiversity, water, and pollution. However, no single action is sufficient to ensure a healthy, just, and sustainable food system. Comparing 2050 values with the current state (as of 2020), a shift to healthy diets in isolation could lead to a 15% reduction in agricultural emissions, compared with a 20% reduction when all three actions are implemented simultaneously with improvements in productivity and food loss and waste. Individually, all three actions modestly reduce future nitrogen and phosphorous use (ie, a 27–34% increase by 2050 with individual actions *vs* a 41% increase under the business-as-usual scenario); however, in combination they substantially reduce future growth in nitrogen and phosphorous use (ie, a 15% increase compared with 2020 levels of use).
- Additional environmental benefits are accrued through sustainable and ecological intensification practices. Unprecedented investments and effort in these practices could potentially result in a net-zero food system. A diversity of context-specific practices can sequester additional carbon biomass, create and connect habitats, reduce nutrient applications, and increase the interception and capture of excessive crop fertiliser before it pollutes groundwater and surface water systems. These practices can be enabled by securing equitable access to land and water resources, strengthening public advisory services, addressing structural imbalances between producers and dominant agribusinesses, and through public and private sector investments that support farmers shifting towards sustainable practices.
- A food systems transformation following recommendations from the EAT–*Lancet* Commission could lead to a less resource-intensive and labour-intensive food system that can supply a healthy diet for 9·6 billion people, with modest impacts on average food costs. However, such a transformation would have profound implications for what, how, and where food is produced, and for people involved in these processes. For example, as a part of this restructuring, some sectors would need to contract (eg, a 33% reduction in ruminant meat production) and others would need to expand (eg, a 63% increase in fruit, vegetable, and nut production) compared with 2020 production levels.

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- Justice is needed to unlock and accelerate action for transformation. A fair distribution of opportunities and resources—such that the rights to food, a healthy environment, and decent work are met, and distribution of the responsibility to produce, distribute, and consume healthy diets within planetary boundaries is fair—are the basis of a successful food systems transformation. Power asymmetries and discriminatory social and political structures prevent these rights from being met, which results in harms to people's health, precarious livelihoods for food systems workers, and lack of voice, undermining freedom, agency, and dignity. Ensuring liveable wages and collective bargaining, while regulating and limiting market concentration and improving transparency, accountability, representation, and access to information, are all impactful actions. We emphasise the protection of basic human rights in conflict areas as a fundamental foundation of justice.
- Unprecedented levels of action are required to shift diets, improve production, and enhance justice. A just transformation requires building coalitions with actors from inside and outside the food system, identifying bundles of actions, developing national and regional roadmaps for implementation, unlocking finance for the transformation, and rapidly putting joint plans into action. Such efforts should closely align with other sustainability and health initiatives (eg, the Paris Agreement, Kunming–Montreal Global Biodiversity Framework, and nation-specific food-based dietary guidelines). These frameworks have all identified food systems actions as powerful, particularly in their capacity to integrate across goals. Mobilising and repurposing finance is essential for enabling this transformation.

human rights framing that includes the rights to food, a healthy environment, and decent work. Analyses reveal important inequities in access to healthy diets, decent work conditions, and healthy environments, disproportionately affecting marginalised groups in low-income regions. We therefore propose nine social foundations that enable these rights to be met, and are able to assess the global status of six. Enabling access to, affordability of, and demand for healthy diets is paramount. Equally crucial is the right to live and work within a non-toxic environment and a stable climate system, as we recognise the profound impact of environmental degradation on human health and wellbeing. Furthermore, a living wage and meaningful representation would allow individuals to actively participate in building healthy, sustainable, and just food systems. However, nearly half of the world's population falls below these social foundations, undermining their ability to meet basic human rights. At the same time, the dietary patterns of most (6·9 billion people) of the world exert pressures that threaten further planetary boundary transgression. The destabilising effect of unhealthy overconsumption on the Earth's systems highlights the importance of viewing healthy diets not just as a human right, but also as a shared responsibility.

Scenario results from an ensemble of 11 global food system models across multiple scenarios reveals the substantial potential for reducing negative environmental and health effects through dietary shifts, improved and increased agricultural productivity, and reductions in food loss and waste. Creating demand for and increasing adoption of diets that adhere to the PHD, coupled with ambitious climate mitigation policies, would result in substantial reductions in greenhouse gas emissions and land use. The results of this modelling excercise are sobering, showing that even with these ambitious transformations (ie, improved and increased agricultural productivity, reduced food loss and waste, and a transition to eating within the PHD), the world is barely able to return to the safe space for freshwater use and climate change, and continues to transgress the biogeochemical boundary for nitrogen and phosphorus loading—albeit with substantially reduced pressure.

Analyses focusing on sustainable and ecological intensification of food production practices, along with more circular nutrient systems, suggest that widespread adoption of these practices could reduce further greenhouse gas emissions, increasing carbon sequestration; reduce the land footprint dedicated to food production; decrease water footprints; and make substantial progress in addressing nitrogen and phosphorus boundary transgressions, even with a growing global population and increased food consumption.

To advance towards the goals of healthy (through the PHD), sustainable (within food system boundaries), and just (above social foundations) food systems by 2050, we propose eight priority solutions, each accompanied by specific actions and policy measures: (1) create food environments to increase demand for healthy diets, ensuring they are more accessible and affordable; (2) protect and promote healthy traditional diets; (3) implement sustainable and ecological intensification practices; (4) apply strong regulations to prevent loss of remaining intact ecosystems; (5) improve infrastructure, management, and consumer behaviour change to reduce food loss and waste; (6) secure decent working conditions; (7) ensure meaningful representation for all; and (8) recognise and protect marginalised groups. These proposed solutions and actions should be organised into coherent bundles to enhance political feasibility and policy effectiveness. The most suitable and effective bundles will vary by context and should be tailored to the specific challenges and opportunities of each region and sector.

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This Commission reinforces the urgent need for a great food transformation. The targets of the EAT–*Lancet* Commission for healthy people on a healthy planet with just food systems can only be met through concerted global action and unprecedented levels of transformative change. The Commission calls for cross-sectoral coalitions that develop context-specific roadmaps, aligning with existing and emerging global frameworks, such as the Paris Agreement, the Convention on Biological Diversity, and the post-2030 Sustainable Development Goals agenda. These roadmaps include the setting of science-based targets with monitoring and accountability mechanisms in place. Mechanisms should be established to shield policy making from undue corporate influence, and civil society and social movements have an important role in promoting transparency and oversight.

Substantial financial resources, estimated between US$200 billion and $500 billion per year, are needed to support the transformation to healthy, sustainable, and just food systems. However, evidence suggests that the price of action is much lower than the cost of inaction, and that investments would rapidly shift to economic benefits (approximately $5 trillion per year). Existing investments can be repurposed by realigning incentives with goals, such as shifting financial support to producer communities adopting sustainable ecological intensification practices or transitioning to the production of underconsumed food groups, and eliminating support for polluting practices or for foods whose overproduction drives poor health.

This Commission positions justice as both a goal and a driving force for a food systems transformation. Food systems cannot be just without ensuring healthy diets that meet the PHD are affordable and accessible, and without reducing planetary boundary transgressions. Justice is also needed to overcome the deeply entrenched structural barriers that currently impede transformative change. Justice is not only an outcome of a food systems transformation, but a prerequisite for enabling it.

Glossary

Planetary health diet
The planetary health diet (PHD) represents a dietary pattern that supports optimal health outcomes and can be applied globally for different populations and different contexts, while also supporting cultural and regional variation. The PHD is rich in plants: whole grains, fruits, vegetables, nuts, and legumes comprise a large proportion of foods consumed, with only moderate or small amounts of fish, dairy, and meat recommended. The PHD is based entirely on the direct effects of different diets on human health, not on environmental criteria. The diet's name arose from the evidence suggesting that its adoption would reduce the environmental impacts and nutritional deficiencies of most current diets.

Food system boundaries
Food system boundaries are science-based targets representing the food system share of the safe operating space within planetary boundaries. These boundaries are based on the available evidence representing the degree of contribution needed from the food system to return or remain within planetary boundaries, including the present-day contribution of food systems to planetary boundary transgressions in relation to other sectors, estimates of minimum environmental impacts from food systems that are hard to abate (ie, through optimisation modelling across sectors), and estimates of reduced Earth system impact while also retaining productive agricultural systems.

Sustainable and ecological intensification
Sustainable intensification entails achieving important reductions in the environmental impacts of food systems though increased efficiency, reduced losses, and reduced pollution. Ecological intensification is a subset of sustainable intensification that enhances the environmental performance of food systems by promoting ecological processes within agricultural fields, farms, and landscapes, such as above-ground and below-ground carbon sequestration, nutrient cycling and storage, pollination, and biological pest regulation.

Social foundations
Social foundations are the conditions that enable basic human rights—such as the rights to food, a healthy environment, and decent work—to be met for everyone. We build on previous work defining the minimum resources required to avoid resource deprivations and harms, and focus on the minimum conditions that enable people's human rights to be met, such as healthy and affordable diets, healthy food environments, a safe climate, a non-toxic environment, living wages, and meaningful representation.

Great food transformation
An unprecedented global commitment to an interlinked range of actions to be taken by all sectors to make healthy food accessible to all, and produced, processed, distributed, and consumed fairly within planetary boundaries.

Introduction: healthy, sustainable, and just food systems

The food system has an outsized impact on human wellbeing and planetary health. What we eat, and where and how this food is produced, processed, and distributed, strongly influences the length and quality of people's lives, and our capacity to stay within planetary boundaries. How food systems are governed and managed determine the extent to which people can participate in and benefit from food systems. Since the 2019 publication of *Food in the Anthropocene: the EAT–*Lancet *Commission on healthy diets from sustainable food systems*,[1] evidence from a growing number of sources show an alarming rise in stress to all natural systems on Earth, escalating diet-related ill health worldwide, worrying inequalities in food consumption patterns within and between countries, and disrupted food supplies. Given this context, and the expected global population increase to approximately 9·6 billion people in 2050, the need and urgency for a food systems transformation to remain within 1·5°C of global warming and to meet global goals related to human health, environmental sustainability, and social justice is clear.

Unsustainable food systems threaten the functioning of the biosphere and the stability of the entire climate system, and underpin unhealthy diets, which account for approximately 15 million avoidable deaths each year (panel 1). Access to food is inequitable, with insufficient access to healthy diets.[6–8] The food system produces enough calories to feed the world's population, but average diets tend to be of low compositional quality, with a global underconsumption of whole grains, fruits, nuts, and vegetables.[6,9] Unhealthy overconsumption, notably of red meat, is a leading driver of climate and land-use impact.[1] Our food supply is inherently sensitive to water scarcity and climatic variability, and is increasingly vulnerable to extreme events such as droughts, floods, heatwaves, or pest or disease outbreaks—all of which are induced by human-driven climate change. Prevailing food production practices are driving biodiversity loss, water scarcity, overuse of pesticides, overloading of fertilisers, climate change, and excessive use of antimicrobials. Food prices do not reflect the true cost of unsustainable production, and rising prices, persistent poverty and economic inequality, and falling wages make healthy diets too expensive for billions of people.[10,11] These factors are a major challenge, as society currently fails to pay for the many negative environmental externalities (eg, climate change, biodiversity loss, and water and nutrient pollution) stemming from unhealthy overconsumption, while almost one billion people suffer from undernutrition. The economic costs of these challenges are staggering: although the global food system generates US$10 trillion in value each year, its negative externalities are estimated at $15 trillion, with the health sector contributing the most.[12,13]

These trends in global food production, distribution, and consumption drive environmental pressures, health costs, and unacceptable injustices. The current socioeconomic situation for billions of people worldwide undermines fundamental human rights. Inadequate and inequitable access to safe, sufficient, and nutritious food for more than 30% of the global population[13] violates the right to food, contributing to malnutrition, ill health, and maternal and child mortality.[9] The global food system drives the transgression of multiple planetary boundaries, violating the right to a healthy environment and a stable planet, and resulting in illness and the loss of work, food, and life (figure 1). Many food systems workers are often underpaid and do not receive social benefits, violating their right to decent work and resulting in exploitation and low purchasing power.[17–19] In addition, the lack of representation and freedom of expression due to factors such as poverty, legal status, racism, and gender biases of many food systems workers, along with a high market concentration (ie, several large food system firms influencing decision making, policies, and prices), undermines the achievement of these rights.[20–23]

Growing attention to food systems, but progress is slow

The global food agenda has made substantial progress over the past 5 years. New evidence provides stronger support for the importance of food for human health and planetary stability, and food justice is being increasingly recognised as an integral part of successful food systems transformations. Scientific attention to food systems has surged, with new evidence emerging daily—including more than 12 000 citations of the 2019 EAT–*Lancet* Commission alone (at the time of publication). This evidence spans the development of planetary health diet (PHD) indices,[3,24] national downscaling of dietary impacts on human health and environmental conditions,[25,26] economic analyses of food systems transformation assessments on novel technologies,[27–29] and behaviour change. Most of this evidence supports the 2019 findings, adding new insights and stronger support for food policy and action on public health, and raising public awareness

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***Panel 1:* The planetary health diet and estimated reduction in avoidable deaths among adults**

The potential reduction in avoidable deaths among adults by adopting the planetary health diet (PHD) has been estimated in two ways for this Commission. One approach used an updated comparative risk assessment (CRA) analysis based on relative risks for specific dietary factors and specific disease incidence (eg, red meat intake and type 2 diabetes) with published meta-analyses of cohort studies, with most having a single assessment of diet (appendix 1 pp 35–39). These associations were then applied to country-specific data on diets and cause-specific mortality. In this approach, adoption of the PHD was estimated to prevent about 10 million avoidable deaths per year among adults globally, representing 17% of total mortality.[2] Around 50% of the reduction in avoidable deaths was due to composition-related risks, including increased consumption of whole grains, fruits, vegetables, legumes, and nuts, and less red and processed meat. The remaining 50% was due to anticipated reductions in underweight, overweight, and obesity.

To estimate more comprehensively the potential population-level impact of adopting the overall PHD pattern on mortality, the PHD reference values[1] were used to create the PHD index, a score for the consistency of individual or national diets with the PHD pattern.[3,4] The association between individual PHD scores and mortality was estimated from the follow-up of over 200 000 adults for more than 30 years; diet was assessed every 4 years to account for changes in food consumption over time and to reduce measurement errors (appendix 1 pp 22–23).[5]

After the relative risks for PHD scores and mortality were combined with the same data on country-specific diets and mortality used for the CRA analysis, an estimated 15 million deaths per year among adults (27% of total deaths) were found to be avoided globally by achieving a PHD score of 120 (with 140 being perfect consistency).[4] This estimate did not include assumptions about reductions in overweight or obesity; including such benefits would result in greater reductions in mortality. When only the baseline dietary assessment was used in the follow-up study, about two-thirds of the mortality reduction was missed. Because achieving a global PHD score of 120 is ambitious, we also estimated the potential benefit of achieving a score of 100 (ie, only 15 points above the scores of current diets); here, the estimated reduction of avoidable deaths was 7 million annually (13% of total deaths).

In both the CRA and the PHD pattern analyses, effects of sodium intake were not included due to difficulties in measurement, and both analyses did not include the indirect effects of diet mediated by environmental impacts of food production. Both analyses used data primarily from high-income countries for estimating relative risks because studies from other world regions are currently scarce, representing an important research gap that should be addressed. However, much evidence supports that relative risks for diet and health outcomes are quite generalisable across populations. Additional benefits due to substantial improvements in diet quality are also likely for children, but these are difficult to estimate quantitatively because of major interactions between diet and infectious diseases, which are particularly important in low-income and middle-income countries.

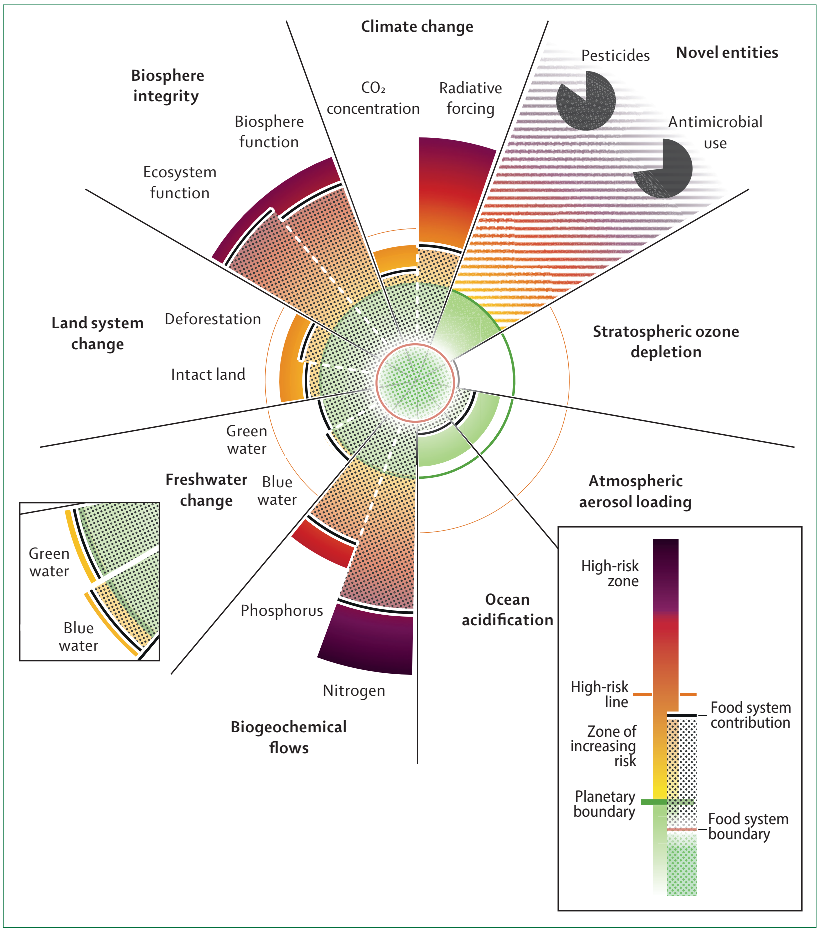

***Figure 1:* Status of food system pressures across all nine planetary boundaries (indicated by the black dotted pattern) and the food system boundaries (red line)**

The food system boundaries are normalised in relation to planetary boundaries (green sphere). The radar plot is adapted with permission from Richardson et al (data)[14] and Rockström et al (visual).[15] The food system contribution (in percentages) is projected based on the wedges' lengths, starting from the planetary boundary for the six transgressed boundaries, and the food boundary for the three other boundaries (see te Wierik et al[16] for details). The food system's contributions to pesticides and antimicrobial use are shown as pie charts (with the food system share in grey) within the larger set of all novel entities (which were previously unquantified). Note that CO_2 concentration is provided in terms of CO_2 equivalents, as in table 2. Adapted from te Wierik et al.[16]

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on the interdependence of food, health, and climate. However, the evidence also signals the need for additional attention to socioeconomic drivers and lock-ins inhibiting change, and to impacts of food across all nine planetary boundaries, rather than the more singular focus on climate.[30]

In addition to growing attention by the research community, many international, national, and local stakeholders are driving various commitments and iniatives. A key moment came in 2021, with the UN Food Systems Summit. Since this summit, two-thirds of countries have adopted national food systems transformation pathways and have made commitments to integrate foods into their Nationally Determined Contributions to the Paris Agreement. More than 290 cities (with a combined population of 490 million people) have signed onto the Milan Urban Food Policy Pact, enacting more than 620 specific food system actions. Both the Intergovernmental Panel on Climate Change (IPCC) and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) have assessed food systems,[31,32] noting the dependency and impact of food on biodiversity, climate, water, and health. The Kunming–Montreal Global Biodiversity Framework, adopted by 196 countries at the UN Biodiversity Conference in December, 2022, set specific food system targets in which food is recognised as uniquely central in the nexus of human health, social justice, and environmental sustainability.[33] We are alarmed by recent efforts to undermine, hide, or obfuscate climate science, environmental protections, and attention to justice. Ignoring these trends aggravates—rather than resolves—the challenges they represent and their growing impact on human society.

Critical scientific assessment

The growing attention to food systems in science and practice is encouraging. However, most emerging national food system pathways have targets that are poorly articulated, non-specific with no accountability, insufficiently ambitious,[34] include too few and siloed interventions,[35–37] and lack appropriate financial support. The slow rate of action is unjust and dangerous to both current populations and future generations.[38,39] Considering this surge in evidence and growing interest in food system actions, an updated assessment is greatly needed. Our primary objective of this Commission is to provide that update.

First, we review the evidence on diet and health published since the first EAT–*Lancet* Commission to provide the latest scientific update on the PHD, paying specific attention to research on dietary patterns and incorporating evidence from a broad range of populations and world regions. We highlight long-established or traditional dietary patterns that are in line with the PHD and emphasise the potential of achieving culturally diverse healthy diets. However we also recognise that modern diets, when configured to the PHD, are equally healthy. The diversity of fruits, nuts, vegetables, and whole grains available in many modern societies, and the interest in ethnic cuisines from around the world, is unprecedented, as is the number of choices available to people favouring healthy options. In addition, we provide updated health impacts and nutritional assessments of adopting the PHD and its related dietary patterns by country and sociodemographic group.

Second, we review the evidence on the effect of food production systems on the Earth system and assess the current state of the global food system across all nine planetary boundaries, updating the five quantified in the 2019 EAT–*Lancet* Commission. For the first time, we propose specific food system boundaries, as the global food system's share of the safe operating space provided by the planetary boundaries, for use in target setting within food systems. We provide a novel assessment of how sustainable and ecological intensification food production practices can support a transformation of food production systems within safe food system boundaries.

Third, we establish social foundations of a just food system and assess where current food systems are placed in relation to these foundations. By adding a focus on justice, we place people at the centre of food systems, recognising that a just food system is one where the human rights to food, a healthy environment, and decent work can be met. We assess the global distribution of injustices, focusing both on where unhealthy food consumption exerts undue pressure on planetary boundaries, and on regions where social justice in relation to the food system are not met.

Fourth, we include a multimodel analysis to quantify the consequences of a food systems transformation to healthy diets, sustainably produced by 2050. We include ten well established agroeconomic and environmental models, with socioeconomic rebound effects to expand our understanding of the potential outcomes of the proposed food systems transformation, including direct effects on food production quantities and environmental impacts, and a greater consideration of potential socioeconomic impacts.

Finally, based on the reviewed evidence, we propose solutions and actions to ensure access to, and demand for, healthy, sustainable, and just food systems for all. Although these solutions are impactful in making healthy and sustainable diets available, accessible, and affordable, we emphasise that these foods offered should also be delicious and desirable to ensure that demand helps fuel their adoption. We also discuss steps to develop roadmaps that can guide and accelerate the urgent and systemic food systems transformation needed.

Although the challenges are daunting, we feel that achieving access to healthy diets for all, which are produced, processed, distributed, and consumed fairly within planetary boundaries, largely remains biophysically possible. Important synergies exist between economic, social, and environmental interventions and outcomes, but are overlooked in current socioeconomic and sociopolitical systems and should be better leveraged. Healthy diets are not only a fundamental right, but a shared responsibility. Major efforts are needed to manage an increasingly urgent food systems transformation that secures human and planetary health, addressing the critical lock-ins (eg, power imbalances and concentration by a few large companies, and weak incentives for disease prevention compared with substantial capital investment in treatment) and political economies inhibiting progress on this necessary transition. The urgency to accelerate the "great food transformation"[1] needed is undeniable. This Commission provides clear quantitative guidance on health, sustainability, and justice, with the aim of helping food systems actors to navigate this progress with greater confidence and impact. The transformation needed to achieve healthy, sustainable, and just food systems is huge, and will require global efforts from individuals, organisations, and governments at all levels of society.

Treatment of uncertainty

As with the 2019 Commission, we recognise that few decisions on dietary health, environmental sustainability, and social justice can be made with absolute certainty. Existing evidence is often incomplete, imperfect, and evolving. This Commission reviews how knowledge has evolved over the past 5 years as a way of reducing this uncertainty. We have based our estimates on the best science available, acknowledging uncertainties where they exist. Confidence levels are provided and improved through wider systematic reviews and broader community efforts to test the validity of findings. For example, a new contribution of this Commission's work is a multimodel intercomparison involving ten global food system modelling teams. These teams have tested the contribution of adopting the PHD and transitioning to more sustainable food production practices, to feeding humanity within planetary boundaries (featured in section 4). Considering the 2019 Commission, and the new research summarised here, we have a high level of scientific confidence about the overall direction and magnitude of food systems transformation required, although considerable uncertainty exists around some of the more detailed quantifications. Our modelling work considers major trends and opportunities; however, food systems actors might choose to navigate this transition in myriad ways, and we encourage them to explore these pathways.

This Commission provides scientific measures for healthy, sustainable, and just food systems based on our current understanding. The models are our current best estimates of some of the implications for human and planetary health of achieving an EAT–*Lancet*-aligned food systems transformation. However, the impacts of such a food systems transformation would also depend on the transition pathways adopted by individual societies. We do not provide historical analysis of the current context, but do evaluate a broad range of solutions with demonstrated impacts in the research literature and encourage food system actors to urgently evaluate and adopt appropriate solutions to their contexts. We remind readers that the PHD and the food system boundaries merely provide healthy and sustainable boundary conditions, within which numerous food dietary compositions and practices fit. Prescribing which actions should be adopted in each location is beyond the scope of this Commission, but we recognise and emphasise the need for greater interactions between scientists, policy makers, and practitioners in finding context-specific solutions.

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See **Online** for appendix 1

Section 1: what is a healthy diet?

Here, we review the evidence on diet and health and present reference values for food group intakes in the reference PHD (table 1). Following the findings of the 2019 Commission, we have included additional health outcomes such as dementia and atrial fibrillation, considered the effects of food processing, and examined the implications of the PHD for young children and women of reproductive age. The relation between the PHD with mortality and other health outcomes has now been examined in numerous epidemiological studies that we summarise. This section also describes gaps between current dietary intakes and the PHD in different regions, and how different dietary cultures might align with the PHD.

	Per capita recommended intake (g/day [range])	Per capita recommended intake (kcal/day)
Plant foods*		
Whole grains†	210 (20–50% of daily energy intake)	735
Tubers and starchy roots‡	50 (0–100)	50
Vegetables§	300 (200–600)	95
Fruits¶	200 (100–300)	145
Tree nuts and peanuts	50 (0–75)	275
Legumes‖	75 (0–150)	275
Animal-sourced foods**		
Milk or equivalents (eg, cheese)	250 (0–500)	145
Chicken and other poultry	30 (0–60)	60
Fish and shellfish††	30 (0–100)	25
Eggs	15 (0–25)	20
Beef, pork, or lamb	15 (0–30)	45
Fats, sugar, and salt		
Unsaturated plant oils‡‡	40 (20–80)	355
Palm and coconut oil	6 (0–8)	55
Lard, tallow, and butter§§	5 (0–10)	..
Sugar (added or free)	30 (0–30)	115
Sodium	<2	..

Most foods are assumed to be unprocessed or minimally processed. At the individual level, the optimal energy intake to maintain a healthy weight in adults and growth in children depends on body size, level of physical activity, and physiological status (eg, pregnancy or lactation in women). The targets, ranges, and options in this flexitarian version of the planetary health diet are intended to provide flexibility within a specific energy intake, with intake of animal-sourced foods not to exceed approximately two servings per day, with one being dairy (250 g milk or milk equivalents) and one being non-dairy (eg, 75–100 g from fish, poultry, red meat, or eggs). Various versions of this dietary pattern, including specific vegetarian, vegan, or pescatarian diets, those of different food cultures, and with different total energy intakes are described in appendix 1 (pp 24–25). *Mostly whole, unprocessed, or minimally processed foods; when processed, added sugar, refined starch, saturated fat, and sodium should be minimal. †Whole-grain rice, wheat, maize, oats, millets, sorghum, and other whole grains are all interchangeable and replace refined grains. ‡Examples include potatoes, yams, cassava, sweet potatoes, and taro. §Combinations of dark green, red and orange, and other vegetables, including aquatic plants. ¶All fruits and berries. ‖A variety of legumes is desirable; for calculations we used 50% soy and 50% other legumes (eg, dry beans, lentils, chickpeas, and peas). **Beef, lamb, and pork are interchangeable. Red meat, chicken, and other poultry can be replaced with eggs or fish, or other sources of plant protein. Dairy food servings are interchangeable with approximately 30 g servings of poultry, fish, or pork, provided calcium intake is satisfied by other food groups. Foods should be mostly whole, unprocessed, or minimally processed. ††Includes fish and shellfish (eg, mussels and shrimps) from capture and farming. ‡‡Unsaturated oils include olive, soybean, rapeseed (or canola), sunflower, peanut oil, and most other plant or vegetable oils. §§Energy values for butter, tallow, and lard are included with dairy and meats.

***Table 1:* Dietary targets for a healthy reference diet for adults, with possible ranges, for a population-level energy intake of approximately 2400 kcal/day**

Approach to defining healthy diets

Healthy diets should be adequate, diverse, balanced, and moderate.[40] Defining healthy diets for a global population is complicated because nutritional requirements vary by factors including age, sex, body size, physical activity level, pregnancy and lactation, health status, and genetics. However, the effects of diets are similar across ancestry or ethnic groups due to common underlying human biology.[41,42] Here, we focus on diets of generally healthy people aged at least 2 years, although the PHD is also key to resolving health risks in populations facing a high prevalence of undernutrition.

We have described healthy diets as combinations of foods, as this most directly connects health with food production and consumption. Nutrient adequacy is important and included in our analyses, but our primary considerations are specific health outcomes related to insufficient or excessive food intakes, rather than numerical targets for essential nutrients (eg, average requirements or estimated average requirements). Nutrient requirements are largely based on small, short-term studies, and are often not supported by sufficient evidence for long-term overall health. In addition to food groups, we include added fats, sugar, and salt in our description of the PHD as they are substantial components of most diets. Our conclusions assume that most foods are consumed whole, unprocessed, or minimally processed.

Although the PHD is based on the direct effect of diets on health, we also discuss potential indirect effects of diets on health, including antimicrobial resistance, pandemic risk, and those mediated by environmental changes (panel 2). Controlling contaminants of food and water (eg, microbes) is essential but is not comprehensively reviewed here. Although the cost and affordability of diets, and the environmental impacts of their production and consumption, are important issues and influence people's access to healthy diets, these factors do not define what is healthy in a diet. We address those separately in other sections.

Review of evidence on diet and health

The goal of this Commission in defining the PHD is to provide the evidence and a quantitative description of a healthy dietary pattern that can be applied globally for different populations and different contexts, while supporting cultural and regional variation. In summarising evidence and evaluating causality, we considered prospective epidemiological studies, randomised trials with intermediate risk factors as endpoints, and the few available randomised trials with health endpoints (panel 3). Because changes in dietary components by individuals or populations are usually made within a constrained total energy intake, isocaloric substitution analyses comparing specific dietary components, such as red meat versus legumes, nuts, or fish, are particularly informative because these represent realistic dietary choices. A key part of this Commission is the evaluation of the PHD as an overall dietary pattern in relation to mortality and other health outcomes.

Based on this body of evidence, PHD reference values (table 1) were developed to provide a foundation for optimal health outcomes, and to use as a starting point to evaluate global environmental impacts of food consumption that are addressed in subsequent sections. These values should not be considered as exact targets for individuals; instead, they represent approximate ranges and proportions, allowing for potential substitutions to accommodate different total energy intakes and preferences. An updated review of the available evidence is included in appendix 1 (pp 2–23); a summary is provided here.

Dietary energy requirements vary greatly between individuals. We estimated an average global energy intake of 2400 kcal/day for adults based on a new doubly labelled water method, assuming an ideal BMI of 22 kg/m² and an "active" level[84] of physical activity (appendix 1 pp 26–27).[84] Assuming the current average global physical activity levels and BMI among adults (~25 kg per m²) leads to a similar energy intake.

Grains, including wheat, rice, maize, oats, barley, rye, teff, amaranth, fonio, buckwheat, millets, and quinoa, are the primary sources of energy worldwide and an important source of fibre, protein, and many micronutrients. Consumption of whole grains (ie, 100% of the bran, germ, and endosperm in an intact grain), but not refined (depleted) grains, improves blood

Panel 2: Indirect effects of diet on human health

In addition to the direct effects of diet on human health, food systems and diets also have many indirect effects on health mediated by their environmental impacts on societal factors. Here, we provide some examples mediated by environmental impacts, which we feel merit greater attention by the scientific community.

Climate change has many extensively documented effects on human health, including heat stress; extreme weather events, such as windstorms, flooding, and prolonged droughts, which affect food production, water security, and attendant deterioration in sanitation, putting people at risk of malnutrition; and increases in the areas and number of people affected by infectious diseases such as dengue, malaria, and West Nile fever.[43] Moreover, climate change affects crop yields,[44] nutritional content,[45] and food-based pathogens, with major indirect effects on human health through changes to the availability and affordability of nutritious food.

Air pollution resulting from food production includes small particulate matter and ground-level ozone, which increase rates of cardiovascular, pulmonary, and neurogenerative disease, and premature deaths.[46] Globally, agriculture accounts for 650 000 deaths (or 20%) of mortality related to poor air quality.[47] This mortality is largely due to nitrogen pollution from fertilisers, leading to emissions of nitrogen oxides and nitrogen dioxide pollution, which is associated with around 4 million new cases of paediatric asthma per year.Biomass burning—including from land clearing and cooking fuel, especially in low-income regions—accounts for a smaller proportion of deaths (ie, 164 000 deaths per year; 5% of mortality related to poor air quality). An estimated 3–6% of global exposure to small particulate air pollution could be avoided by adoption of more plant-rich diets, resulting in approximately 100 000–300 000 avoidable deaths annually.[48]

Nitrogen pollution of drinking water due to excess fertiliser use has been associated with methemoglobinemia, colorectal cancer, thyroid disease, and birth defects.[49] Other adverse effects of nitrogen pollution in waters could be compounded by eutrophication of water bodies and overgrowth of toxic algal blooms.[50] The groundwater threshold for nitrogen pollution is exceeded in 38% of agricultural lands globally,[51] particularly affecting the health of vulnerable rural populations with strong groundwater dependencies.

Biocides (including pesticides, herbicides, and fungicides) are used extensively in agriculture.[52] Although biocides are regulated in most countries to prevent risks to human health, their misuse (ie, overapplication or inadequate protective measures, particularly for agricultural workers), and co-exposure resulting from mixtures in the environment, has multiple adverse effects on health.[53] Chronic exposure to pesticides, including by consumption of contaminated foods, is associated with increased risks of Parkinson's disease, diabetes, cancer, cardiovascular disease, and possibly with infertility.[54]

Antimicrobial resistance and pandemic risk have increased in part due to increased animal–human contact (either through direct interaction with wildlife or indirectly through vectors or intermediate, domesticated species), which is a prerequisite for zoonotic spillover.[55] The large-scale global increases in consumption of animal-sourced foods that originate from a small number of species, often produced in highly concentrated systems, increases risk.[56,57] Cattle and pigs now make up approximately 43% of the mammalian biomass on the planet (humans make up ~38%),[58] and domestic poultry makes up around 70% of the avian biomass.[59] This large biomass poses a risk for the emergence of novel pathogens affecting humans and animals, and accelerates the frequency of epidemic and pandemic disease events.[60] The scale-up in animal-sourced food production has been enabled by the use of antimicrobials as growth promoters, which are responsible for around two-thirds of antimicrobial production worldwide.[61] The risk of antimicrobial resistance emerging from the use of antimicrobials in animals is well documented,[62,63] and an estimated 1·4 million people die each year from untreatable microbial infections.[64] We estimated that adoption of the PHD would decrease antimicrobial use by approximately 42% due to reductions in animal-sourced foods.[65]

Panel 3: The planetary health diet and health—evidence for causality

Ideally, evidence for the effects of specific foods, nutrients, and overall diets on major health outcomes would be based on large, randomised trials with disease and functional endpoints in representative populations across the world. However, this type of evidence is scarce because such trials require many thousands of participants, many years—or even decades—of follow-up, and sustained high adherence to assigned diets. These requirements are neither feasible nor ethical, and randomised trials not meeting these criteria can easily yield misleading, null, or negative results. Therefore, for studies of diet and other behavioural and environmental exposures, frameworks to assess causality, such as the Bradford Hill criteria,[66] have been developed. For dietary factors, these frameworks typically include reproducible evidence from prospective epidemiological studies (eg, following a cohort over time) in combination with randomised trials that include intermediate risk factors as outcomes.[67] Rigorous control of confounding factors by study design and statistical methods is essential.

The following example illustrates the value of combined evidence from observational and experimental studies in informing the links between the planetary health diet (PHD) and health. A central feature of the PHD is the importance of nuts and legumes—including beans, pulses, and soy—as major protein sources, with small amounts of red meat and dairy foods. The far higher ratio of polyunsaturated fatty acids to saturated fatty acids in these plant foods compared with red meat and dairy products predicts lower LDL cholesterol; this prediction was confirmed in a meta-analysis of randomised trials of red meat intake.[68] In long-term cohort studies with repeated assessments of diet, mortality was lowest when plant protein was compared with red meat, dairy foods, and poultry;[69] associations with type 2 diabetes and coronary heart disease have been similar.[70] Other key features of the PHD include relatively high amounts of fruits and vegetables, which are shown to reduce blood pressure in the Dietary Approaches to Stop Hypertension randomised trial;[71] whole grains, shown to improve blood lipids in randomised trials;[72] and largely unsaturated plant oils, shown to reduce LDL cholesterol.[73] Components of the PHD might also offer additional pathways, such as modulation of the gut microbiome; however, as a minimum, its beneficial effects on firmly established risk factors are clear. As described in the main text, in multiple large cohort studies with careful adjustment for smoking and other potentially confounding variables, participants with diets most consistent with the PHD have had reduced risks of many major health outcomes, including type 2 diabetes, cardiovascular disease, and total mortality.

Important causal evidence for benefits of the PHD also comes from decades of research on the traditional Mediterranean dietary pattern, a specific example of the PHD.[74] In addition to the types of evidence from observational studies and trials of intermediate endpoints described in the previous paragraph,[75] in a large, randomised trial in people with raised cardiovascular disease risk, a Mediterranean diet with added nuts or olive oil reduced the risk of cardiovascular disease,[76] type 2 diabetes,[77] cognitive decline,[78,79] and other adverse health outcomes.[80] In another randomised trial, adherence to a Mediterranean diet reversed the prevalence of a pre-diabetic state by 50% over 1 year,[81] and in a 2-year randomised trial, this dietary pattern reduced bodyweight compared with low-fat or high-fat diets,[82] and weight loss was sustained at 6 years.[83]

lipid values and other biomarkers[85] and is inversely associated with risks of weight gain,[86,87] type 2 diabetes,[88] coronary heart disease,[89,90] colorectal cancer,[89] and total mortality.[91] The inverse association between intake of whole grains and weight appears linear, but a concern is that high intake of whole grains could displace other healthy foods and reduce micronutrient absorption. We therefore used 210 g per day dry weight as a reference value for grains (midway within a ~20–50% share of energy intake), considering this to be flexible and emphasising whole grains versus refined grains.

Tubers, including potatoes, sweet potatoes, taro, yams, and cassava, are a major energy source in some populations, but commonly consumed white potatoes do not provide the amounts of fibre or micronutrients as do whole grains. Compared with whole grains or non-starchy vegetables, consumption of potatoes is associated with greater weight gain[92] and risk of type 2 diabetes,[93,94] and the association is stronger for fried potatoes than non-fried potatoes.[93,94] Data on other tubers are scarce. Because these findings support consumption of whole grains over potatoes as a major energy source, we used 50 g per day as the reference value.

Fruits and vegetables, including seaweeds and other aquatic plants, are a primary source of many nutrients and phytochemicals. Intake is inversely associated with risks of weight gain,[86,95] type 2 diabetes,[6,97] coronary heart disease,[97] some cancers,[98,99] and total mortality.[100] Evidence also shows a reduced risk of cognitive decline and dementia associated with fruit and vegetable intake.[101–103] Because of differences in the composition of specific fruits or vegetables and their distinct associations with health outcomes, consuming a variety is desirable, specifically including green leafy and dark orange foods. Most health benefits accrue with about five servings per day; we used 500 g per day as the reference value, with no specified upper limit.

Nuts, legumes, and seeds provide protein, unsaturated fats, fibre, and many micronutrients. Nuts and legumes have beneficial effects on blood lipids,[104] and consumption of nuts, including peanuts, has been associated with reduced risks of type 2 diabetes,[97] coronary heart disease,[97,105] and total mortality.[106,107] Soy foods contain substantial amounts of both omega-3 and omega-6 fatty acids and are uniquely high in phytoestrogens, and consumption has been associated with reduced risks of cardiovascular disease[108,109] and breast cancer.[110] As nuts and legumes are healthy sources of protein, the reference value includes 125 g per day dry weight (about 3–5 servings per day of legumes, nuts, and seeds, including at least one serving of nuts); a variety is encouraged.

Red (mammalian) meat is high in protein, haem iron, and other minerals, but is also high in saturated fat and cholesterol and low in essential polyunsaturated fatty acids. In populations consuming very high amounts of carbohydrates, small amounts of red meat or other animal-sourced foods can provide essential nutrients that have positive health benefits. Consistent with their fatty acid composition, and compared with plant sources of protein (eg, nuts, soy, and other legumes), consumption of red meat increases blood levels of LDL cholesterol[68,85] and is associated with increased risk of coronary heart disease.[97,111] Furthermore, consumption of red meat is linearly associated with an elevated risk of type 2 diabetes among different populations, including those in Asia, Europe, and North America; both unprocessed and processed red meat contribute to this increased risk, but the latter's association is stronger.[42,112] Red meat intake has also been positively associated with unhealthy weight gain and risks of gestational diabetes,[112] colorectal cancer (especially for processed red meat),[113] frailty,[114] and unhealthy ageing.[115,116] Red meat consumption is associated with increased risk of total mortality in countries that have been consuming high amounts for many decades.[117]

Because the association of red meat with type 2 diabetes has been documented in many large studies,[42,97,111,112,118–120] and because diabetes is a sentinel disease for many adverse cardiometabolic outcomes, this dose–response relationship was used to determine the reference value in table 1. According to data from three large US cohorts with over 22 000 incident cases of diabetes and many repeated measures of diet over three decades, the relationship between increased red meat consumption and increased diabetes incidence is approximately linear; where little or no red meat is consumed, diabetes risk is lowest.[121] We used 15 g per day (about one serving per week) as the reference value, with a range including zero to allow a modest intake while avoiding statistically significant increases in risk (see appendix 1 pp 6–10 for further details).

Poultry meat has similar nutritional values to red meat, but its polyunsaturated fat composition is somewhere between that of red meat and plant protein sources. Associations with risks of non-communicable diseases and mortality have also generally been intermediate;[42,122,123] an inverse association with stroke has been an exception.[97] Because these relationships suggest prioritising poultry over red meat, we used 30 g per day of poultry (about two servings per week) as the PHD reference value.

Eggs are a concentrated source of protein and essential nutrients and can have an important role in childhood diets. They are also high in dietary cholesterol and have generally shown no clear association with non-communicable disease risk,[124,125] except for positive associations with risks of coronary heart disease in people with diabetes.[126,127] Consistent with other guidelines, we used 15 g per day (about two eggs per week) as the reference value.

Milk and its derivatives have broad nutritional values but are high in saturated fat and low in polyunsaturated fat. Its high calcium content has been a primary justification for substantial lifetime consumption; however, calcium requirements for adults have been based on short-term studies, and milk intake has not been clearly related to reduced risk of bone fractures.[128] Consistent with its fatty acid composition, dairy fat substantially increases LDL cholesterol compared with unsaturated plant oils.[129] Epidemiological evidence is largely based on cow milk; as predicted, dairy fat is positively associated with cardiovascular disease.[130] Risks of cardiometabolic disease[97] and overall mortality[131,132] associated with milk intake are somewhere between the risks of red meat and healthy plant sources of protein. Dairy consumption is associated with low risks of colorectal cancer[133] but elevated risks of prostate cancer.[134] Some evidence suggests that yoghurt consumption, and possibly other fermented products, might be associated with less weight gain[135] and reduced risk of type 2 diabetes[97] compared with other dairy foods. We used 250 g per day of milk or the equivalent amount of milk derivatives (ie, one serving per day) as the reference value because of its intermediate relation with non-communicable diseases risk and substantial contribution to calcium intake; the range includes zero because many populations globally do not consume milk and still have low fracture risk.[128] In a 2025 meta-analysis, a small decrease in cardiovascular disease risk was observed in people who consumed about one serving of dairy per day, especially low-fat milk and cheese, but little further change in risk was seen with higher intakes.[136]

Fish, shellfish, and other aquatic animal-sourced foods are major sources of protein and essential nutrients for many populations, including in low-income and middle-income countries. In many diets, small fish and bivalves are often overlooked as potential foods. Collectively, these foods are particularly important as a source of omega-3 fatty acids (which are minimally present in terrestrial animal-sourced foods); low intakes of omega-3 fatty acids can slow down neurological development in childhood[137] and possibly increase the risk of cognitive decline in adults;[138] high intakes of omega-3 fatty acids are associated with reduced risk of cardiovascular disease.[139,140] The relationship between intake of fish or omega-3 fatty acids and cardiovascular diseases appears to be non-linear;[139] most of the benefit is achieved with 30 g per day of fish (about two 100 g servings per week), which is used as the reference value.

Evidence from prospective cohort studies and randomised trials has not suggested a reduction in cardiovascular disease[141] or cancer[142] by decreasing total fat intake. However, added fats differ greatly in their composition and health effects; partial hydrogenation creates deleterious trans isomers that are associated with increased risks of cardiovascular diseases[143] and all-cause mortality,[144] and this process is now banned in many countries.[145] Non-hydrogenated plant oils that contain mainly unsaturated fatty acids reduce LDL cholesterol,[146] and intake is strongly related to reduced risks of cardiometabolic diseases and total mortality.[147] These inverse associations appear linear within the ranges studied. Palm oil is relatively high in saturated fat and low in polyunsaturated fatty acids compared with other plant oils; although studies of health outcomes are scarce, available evidence favours more unsaturated plant oils.[148] Because non-hydrogenated plant oils have positive health effects, consumption can be flexible within the limits for total energy intake (eg, if exchanged isocalorically with whole grains). We used a reference value of 17% of a person's daily recommended energy intake (primarily as unsaturated plant oils that include both omega-6 and omega-3 fatty acids), similar to that of a Mediterranean diet, which is associated with a reduced incidence of cardiovascular disease.[76]

Added or free sugars provide no nutritional value and can cause harms when excessively consumed. Intake, particularly in the form of sugar-sweetened beverages, has adverse cardiometabolic effects and has been positively associated with weight gain,[149] type 2 diabetes,[150] coronary heart disease,[151] and total mortality.[152] Consistent with conclusions of WHO[153] and many national guidelines, a maximum intake of 5% of energy from added or free sugars is used as a reference value.

Sodium, commonly consumed as salt or monosodium glutamate, is essential, but intake greater than 1500 mg per day increases blood pressure, and intake greater than about 2000 mg per day is linearly associated with an increased risk of cardiovascular disease.[153] We therefore used an intake of up to 2000 mg per day of sodium (5 g per day as salt) as the PHD's reference value.

Minimal processing, such as drying grains, pulses, and nuts; chilling or freezing fruits and vegetables; and pasteurising milk and fermenting milk into yoghurt, reduces food microbial contamination, extends freshness, enhances sensory properties, adds variety to diets,[154] and reduces the time and labour costs of food preparation. Food fortification can improve micronutrient density, especially for nutritionally vulnerable populations. However, processing can also have adverse effects, including a reduction in food nutritional content, addition of excessive salt and sugar, and use of unhealthy fats and refined grains. Processes that destroy the structure of whole foods, chemically alter their components, and assemble them with various sensory-related additives into products that are liable to displace unprocessed or minimally processed foods and freshly prepared dishes and meals, are considered ultra-processing.[154] Diets high in ultra-processed foods have been associated with 32 adverse health outcomes spanning mortality, cancer, and mental, respiratory, cardiovascular, gastrointestinal, and metabolic health effects.[155] Our Commission concludes that most foods should be consumed whole, unprocessed, or minimally processed.

Overall dietary patterns and health

Evaluations of overall dietary patterns in relation to their risk of health outcomes represent the combined effects of all dietary components, including their interactions (appendix 1 pp 22–23). Dietary patterns have been developed to describe traditional diets of specific regions or cultures (eg, Mediterranean or Japanese)[156,157] through the use of statistical approaches, such as principal components or reduced rank regression analysis,[158] or, as for the PHD, based on available evidence relating dietary components to health outcomes.

In meta-analyses, dietary patterns similar to the PHD were associated with reduced risk of all-cause mortality.[159,160] Within three large cohorts, the Mediterranean dietary score and five other commonly used indices of diet quality were similarly inversely associated with overall mortality and a composite outcome of major chronic diseases.[161] Within-person improvements in dietary quality scores over time were associated with reduced risks of all-cause mortality.[162] These and other dietary patterns have also been associated with many other outcomes, including reduced risks of depression and dementia.[163,164] Over the past three decades, supported by extensive analyses in many populations, a substantial convergence has developed over the broad definition of a healthy dietary pattern.

Since the 2019 Commission, multiple investigators have created indices representing consistency with the PHD, which is strongly correlated with other dietary quality indices.[3,165] In prospective studies worldwide, significant inverse associations were reported for the PHD and numerous health outcomes, including total cardiovascular diseases, ischaemic heart disease, myocardial infarction, atrial fibrillation, stroke, heart failure, type 2 diabetes, obesity, and cancers (eg, lung and colorectal). Some reported null associations, but these findings need to be placed in the context of methodological limitations (see appendix 1 pp 22–23).[166–168] In an analysis of 206 404 adults followed up for up to 33 years, over 54 000 deaths were documented; overall mortality in the highest decile of adherence to the PHD was 28% lower compared with overall mortality in the lowest decile (appendix 1 pp 22–23).[3] Although findings on the association between the PHD and mortality in two cohorts of Chinese adults[169,170] are consistent with results from the USA and Europe (appendix 1 pp 22–23), data from low-income and middle-income countries are limited by the absence of large cohort studies in most regions. Associations could vary depending on dietary preferences within food groups, and further research from these areas is needed.

Table 1 presents reference values of the PHD pattern for flexitarian adults. Scenarios for vegetarian or pescatarian dietary patterns and different total energy intakes are presented in appendix 1 (pp 24–25). The PHD pattern described in this Commission is not substantially different from the 2019 Commission.[1] The dietary components in table 1 have been reordered to facilitate interpretation, with slight rounding of several numbers. Total population-level adult energy intake is specified at 2400 kcal per day (instead of 2500 kcal per day as in the 2019 Commission) based on updated values (appendix 1 pp 26–27) and the recognition that energy requirements vary by individuals.[84]

Nutrient adequacy of the planetary health diet

The primary evaluation of a diet's nutrient adequacy is based on health outcomes, which represent the cumulative consequences of all aspects of diet quality, including the intake of total calories, essential nutrients, and other dietary components, as well as the effects of processing and their interactions. We evaluated the nutrient adequacy of the PHD for adults compared with current diets by pairing estimated intake with nutrient densities and comparing those to the average requirements of each population group (appendix 1 pp 28–31).[171] Current intake was estimated by triangulating waste-adjusted food availability data with data from dietary surveys and estimated energy requirements (appendix 1 pp 33–34).

For most nutrients, the PHD is adequate and performs better than current average diets, especially for fatty acid profiles and intake of protein, free or added sugars, fibre, folate, magnesium, potassium, and zinc (appendix 1 p 29). Intake of calcium, vitamin B12, iron, and iodine from the PHD warrant further attention, especially in populations that have low dietary diversity. Important differences are observed by national income (appendix 1 p 31). In low-income countries (LICs), for example, the required intake of most nutrients in the PHD is substantially higher than in current diets, but in higher income countries, intake of some micronutrients (eg, vitamins B12 and B6) is lower than in current diets but still remains adequate. Optimisation within the PHD reference values for general food groups (eg, by increasing the proportion of green leafy vegetables for iron, fermented soy foods for B12, and algae for B12 and iodine) can ensure nutritional adequacy for all population groups.[2] On average, calcium intake in the PHD is higher than in current diets, but is estimated to be lower than recommended in some countries without optimisation (appendix 1 pp 28–31). However, calcium requirements are likely to be overestimated because they are based on short-term studies.[128] Notably, Indonesia has one of the lowest calcium intake (approximately 250 mg/day) and fracture rates in the world.[128] Global average vitamin B12 intake—which is already somewhat insufficient—was slightly reduced in the PHD when not optimised. Vitamin B12 intake is likely to be low if consumption of all animal-sourced foods is on the lower end of the PHD ranges (eg, in vegan and vegetarian diets) and no supplementary foods are consumed; this merits attention because deficiencies can result in permanent neurological damage.[172] Dietary modifications with traditionally available food sources (eg, fermented soybeans and algae in east Asia, fermented sesame in western Africa, bivalves in coastal areas, and nutritional yeast more widely) can ensure sufficient vitamin B12 intake.[2] In populations with biochemical evidence of inadequate intake, fortification or micronutrient supplementation should be considered.

Absorbed iron intake in the PHD reference diet is similar to the current global average. Absorption efficiency was estimated by accounting for regulatory components such as phytates, vitamin C, and haem and non-haem iron in diets (appendix 1 pp 28–31). The iron needs of women of reproductive age merit specific attention to ensure adequate intake of iron-rich food sources, including legumes, soy products, dark green vegetables, and whole grains (see next subsection). Increases in red meat consumption (as an iron source) above the recommended ranges of the PHD are associated with other adverse health outcomes as outlined earlier and in appendix 1 (pp 6–10). Estimated iodine intake from current diets and the PHD appear marginal, but intake depends strongly on soil composition where foods are produced (ie, their proximity to marine environments) and seafood consumption, including algae.

Absorption of nutrients such as iron, zinc, and vitamin A can be compounded by parasitic and other infectious diseases common in low-income and middle-income countries. Because of complexities in estimated nutrient intake, absorption, and losses, monitoring the prevalence of nutrient deficiency is critical. Improvements in diet quality, together with appropriate fortification (eg, of salt for iodine deficiency) or micronutrient supplementation strategies and non-nutritional interventions (eg, water, sanitation, and infectious disease control), are possible approaches to address nutrient deficiency.

The PHD provides approximately 14% of a person's daily energy intake from protein, which exceeds requirements (estimated average requirement 0·7 g per kg bodyweight; approximately 10% of energy intake), and will provide sufficient essential amino acids.[173] The relationship between protein intake and health outcomes will depend on the protein sources. In a meta-analysis, protein intake was inversely associated with lower overall mortality, but this apparent benefit was entirely due to plant—rather than animal—sources of protein.[174] Marginal increases in protein intake (eg, 15–30% of energy) are thought to be beneficial for older adults.[175] This finding was supported in an analysis on healthy ageing, in which plant sources (rather than animal sources) of protein provided almost all of the ascribed benefits.[176] The PHD provides approximately 53% of calories from carbohydrates and 35% from total fat, which is compatible with the flexible amounts of these macronutrients.

Women of reproductive age

More than one billion adolescent girls and women suffer from undernutrition, anaemia, and other micronutrient deficiencies, which can result in devastating health impacts.[177] The overall health of women of reproductive age is supported by the PHD (table 1; appendix 1 p 37). However, the iron needs of these women warrant merit specific attention due to menstrual loss, pregnancy, and lactation.

A healthy diet during pregnancy is essential to prevent adverse maternal outcomes, support healthy fetal development, and avoid fetal programming that can transmit metabolic dysfunction to future generations.[178] Overall food intake should be adjusted for optimal weight gain and include a variety of healthy foods,[179,180] consistent with the PHD (table 1). Although balanced vegetarian diets can support healthy fetal development,[181] the use of micronutrient supplements or fortified foods might be indicated if consumption of animal-sourced foods is below reference values. Because of extra nutritional demands of pregnancy, WHO recommends[179] routine iron and folic acid supplementation to prevent maternal anaemia and puerperal sepsis, as well as fetal spina bifida and anencephaly. Other context-specific recommendations include micronutrient supplementation (eg, calcium, vitamin A, and zinc) or routine use of multiple micronutrient supplementations during pregnancy, which is now used routinely in many countries because of benefits beyond those provided by iron and folate alone.[182]

Dietary needs of infants and young children

Children younger than 2 years have unique requirements for rapid growth and development. Exclusive breastfeeding, including timely access to colostrum, in the first 6 months of infancy is strongly advised to ensure optimal nutrition, reduce the risk of infectious disease, prevent both undernutrition and obesity, and for other benefits for infants and their mothers.[183] From age 6 months, introduction of safe complementary foods based on diverse, locally available, and nutrient-dense food is essential for optimal growth and development.[184] Continued breastfeeding is important and deserves promotion, protection, and support.

Dietary habits and taste preferences are developed in early childhood, and children should become familiar with healthy foods that form the foundation for a healthy life. Fish, meat, eggs, and dairy foods are rich sources of some key nutrients for children of this age, including iron, vitamin B12, zinc, and calcium.[185,186] These nutrients, except vitamin B12, can also be obtained from typical plant-based food sources, such as nuts and legumes, seeds, and vegetables. The amounts of these animal-sourced foods described in table 1 would be suitable for most young children aged 6–24 months.[183] Lower amounts of animal-sourced foods can result in nutritional deficiencies if not adequately replaced, including vitamin B12 deficiency, which is associated with poor neurodevelopment in young children.[185] For children with animal-sourced food intakes below the PHD reference values, complementing their diet with the use of nutrient supplements or fortified foods can make nutrient intakes adequate.[183,186,187] Minimally processed foods should be prioritised and ultra-processed foods and beverages should be minimised, as most are nutritionally unbalanced and can contain harmful additives.

For more on **examples of healthy meals** see https://eatforum.org/eat-lancet-commission/

Adopting the planetary health diet globally

The components of healthy diets, described broadly with reference values and ranges, and potential exchanges among food groups (table 1), allow great flexibility because they are compatible with a wide variety of foods, agricultural systems, cultural traditions, and individual dietary preferences.[2] Possible ranges for individual components are described, with overall intake of animal-sourced foods being approximately two servings per day. The suggested daily or weekly amounts can be consumed at once or spread out in small amounts; for example, red meat might be consumed as an 80–100 g serving once a week or as small amounts in mixed dishes or soups, as is customary in many recipes.

The balance of healthy animal-sourced and plant-source foods presented in the PHD is consistent with many dietary patterns, including Indigenous diets,[188,189] the well studied Mediterranean diet,[75,157] and other traditional diets worldwide. As with the PHD, these traditional diets have a base of whole grains or tubers, a wide variety of greens and other vegetables, legumes, and small to modest amounts of fish or meat with herbs and sauces that add flavour and nutritional value.[188,190,191] Moreover, many traditional food practices support improved bioavailability of nutrients—such as soaking, fermentation, and combining vitamin C-rich fruits and vegetables with plant-based iron sources—and leverage the seasonality of cultivated and wild food species.[188,189] Although more research on traditional diets in different regions is desirable, many of these patterns are consistent with high dietary quality[192] and low rates of chronic disease. Protecting healthy traditional diets and food systems can be crucial to avoid transitions to unhealthy consumption. Examples of healthy meals based on traditional foods and flavours, and that are consistent with the PHD, are described in appendix 1 (pp 40–43) and on the EAT website.

In settings with humanitarian crises, deep food insecurity, or in populations where diets remain dominated by staple carbohydrates (eg, largely rice or cassava), food supplements, including fortified foods, might be required in addition to improvements to dietary quality.[193,194] The time and labour needed, mainly by women, for food preparation should be considered, and if cooking fuel is in short supply, this can prevent the preparation of nutrient-dense foods, such as legumes. Availability of refrigeration and cooking facilities can also constrain food preparation. In some situations, processed, ready-to-eat foods might be necessary, and care is needed to ensure these are nutritionally balanced. Adequate amounts of safe water for drinking and sanitation are always essential. Achieving PHD-aligned diets represents an important goal for populations with a high burden of undernutrition.

The gaps between PHD reference values and current diets vary greatly among regions (figure 2). Notably, red meat and tuber and starchy root intake is excessive in most regions except south Asia. Tuber and starchy root intake in sub-Saharan Africa substantially exceeds the PHD reference value and is higher compared with other regions. Intake of free or added sugars is higher than the reference value in all regions except sub-Saharan Africa and east Asia–Pacific. In most regions, consumption of many healthy foods is low, including vegetables, fruits, legumes, nuts and seeds, and whole grains (instead of refined grains); increasing consumption of these foods offers important opportunities to improve health.

Conclusions of healthy diets

New evidence, including dose–response relationships, has added substantial support for the health benefits of the PHD described in the 2019 EAT–*Lancet* Commission (appendix 1 pp 2–23).[1] This evidence further supports emphasising whole grains over refined grains and potatoes,[94] plant sources of protein (eg, legumes, pulses, and nuts) over red meat (unprocessed or processed),[97,121] and unsaturated plant oils over saturated fats;[130,196,197] including generous amounts of fruits and vegetables,[98] and moderate amounts of dairy, fish, eggs, and poultry; and limiting free or added sugars and salt.[153,198,199]

The elements of a healthy diet and recommended intake ranges for food groups are purposefully flexible to accommodate various dietary preferences, agricultural systems, and cultures. They can be combined in various types of flexitarian, vegetarian, pescatarian, and vegan diets. The numerous health benefits found in many populations from the PHD and similar dietary patterns show that healthy diets can be achieved in many contemporary populations worldwide.

In making global estimates of effects of diets on health, another general conclusion is that available data on the composition of foods, national dietary intakes, and the relation of dietary factors to health are far from optimal. Notably, large cohort studies with long follow-ups are scarce in Africa, Latin America, and most parts of Asia. Because aspects of diet strongly influence health, enhancements in data availability and quality are needed to provide better precision in future analyses and more specific regional and local dietary guidance.

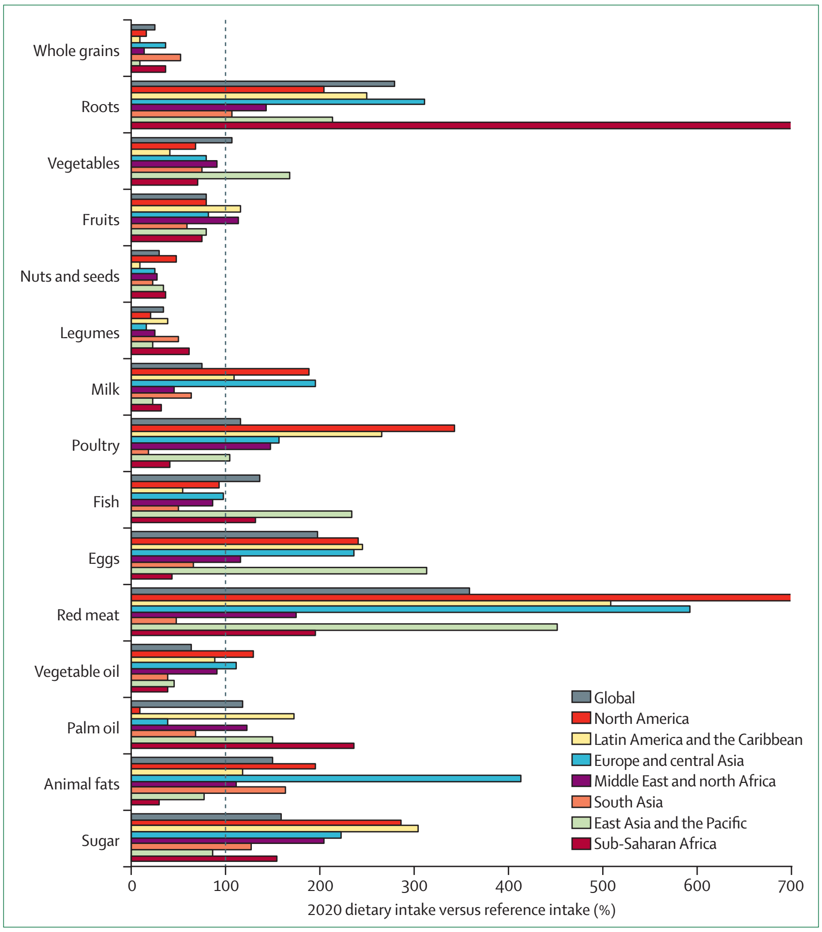


Figure 2: **Differences between adult diets in 2020 and the planetary health diet globally and by region**
The dashed line represents the reference values of the flexitarian version of the PHD from table 1 (see appendix 1 pp 24–25 for source).[195]

Section 2: sustainable food systems within planetary boundaries

Planetary boundaries is an Earth system's framework[200] that quantifies limits for biophysical processes that regulate the stability and resilience of life-support systems on Earth. Transgression of these boundaries pushes the Earth system into an unsafe environmental space for humanity. The latest update of the planetary boundary framework[14] concludes that six of nine planetary boundaries have already been transgressed. The 2019 EAT–*Lancet* Commission assessed five of these boundaries—land, biodiversity, climate, blue water flows, and biogeochemical flows—and found that food systems exert the greatest pressure on boundary transgressions. Here, we re-evaluate the evidence on the effect of food systems on all nine planetary boundaries, including four boundaries not assessed in the 2019 Commission: aerosol loading, ozone depletion, ocean acidification, and novel entities (table 2).

In this Commission, we have quantified the share of planetary boundaries allocated to the food system (ie, food system boundaries; figure 1). In contrast to planetary boundaries, food system boundaries are not based on increasing risk levels in the Earth system, but represent science-based environmental targets for the global food system, aligned with the planetary boundary framework. As no consistent frameworks exist to define such targets, we define food system boundaries based on three principles from existing literature: (1) through proportional reductions necessary to return to the safe operating space (ie, stable and resilient Earth system conditions that support human development) based on the current food system's contributions to transgressions; (2) through top-down sectoral optimisation of mitigation costs by use of integrated assessment models; and (3) by considering food system boundaries as equal to planetary boundaries (based on large uncertainties in the food system share [eg, green water] or on the major contribution of food systems to planetary boundary transgressions). In some cases, food system boundaries are based on evidence that supports maintaining productivity of agricultural systems while reducing their effects on the Earth system (appendix 2 pp 2–11).[16]

See Online for appendix 2

	Planetary boundary	Current state	Current food system state	Food system boundary
Climate change				
Atmospheric CO_2 concentration	350 ppm CO_2	419 ppm CO_2	16–17·7 Gt CO_2e per year (30% of total anthropogenic emissions)	5 Gt CO_2e per year
Total anthropogenic radiative forcing at the top of the atmosphere	1·2 W per m²	2·91 W per m²	24% of total net radiative forcing	..
Land system change				
Area of intact land as a percentage of original cover worldwide[39]	50–60% remaining intactness	50% remaining intactness	48 M per km² (34% of total land surface)	Agricultural land <48 M per km² (requires halting land conversion of intact nature)
Area of intact land as a percentage of original cover by ecoregion[39]	50–60% remaining intactness (with particular attention given to forest ecoregions)	10–95% remaining intactness	33% of ecoregions below the intactness threshold (50%) due to agriculture alone	<40–50% agricultural land at ecoregion level; restoring 8·5 M per km² intactness in forest ecoregions
Biosphere integrity				
Biosphere functional integrity (HANPP)	5·5 Gt C per year (<10% of Holocene NPP)	13–16·8 Gt C per year, (25–30% of Holocene NPP)	9·9–11·7 Gt C per year (72–85% of total HANPP)	5·5 Gt C per year
Ecosystem functional integrity[39]	>20–25% habitat per km² for supporting agroecosystem functioning	30–60% of agricultural lands below boundary	88% of agricultural lands used for food production	100% of all food-producing lands within the boundary
Stratospheric ozone depletion				
Stratospheric O_3 concentration (global average)	<5% reduction from preindustrial level assessed by latitude (~276 DU)	284 DU	3·9–4·2 Tg N_2O-N per year (54–69% of total N_2O emissions)	1·8 Tg N_2O-N
Ocean acidification				
Carbonate ion concentration; average global surface ocean saturation state with respect to aragonite (Ω_{arag})	≥80% of the mean pre-industrial surface ocean Ω_{arag} of 3·44	Ω_{arag} of 2·8	25% of CO_2 emissions; main driver of change in Ω_{arag}	Zero CO_2 emissions from land-use change and fossil energy use in the food chain
Biogeochemical flows: nitrogen and phosphorus				
Nitrogen surplus[51]	57 Tg nitrogen per year	119 Tg nitrogen per year	50, 70, 80% to deposition, surface water load, and groundwater leaching	<57 Tg nitrogen per year (agricultural nitrogen inputs <134 Tg nitrogen per year with current nitrogen use efficiency)
Phosphorus loss to surface water[201]	6·1 Tg phosphorus per year	9·7 Tg phosphorus per year	7·2 Tg phosphorus per year (75% of total delivery)	4·6 Tg phosphorus per year
Freshwater change				
Blue water use (from consumption; km³ per year)[1]	2800 km³ per year	1800–2600 km³ per year	>1200–1800 km³ per year, including groundwater	2000 km³ per year
Green water (percentage of ice-free land area beyond the 5th–95th variability envelope)	11·1% of land area with local deviations	15·8% of land area with local deviations	16·8% of agricultural lands are beyond the local variability envelope	Remaining within pre-industrial variability envelopes on all agricultural land
Atmospheric aerosol loading				
Interhemispheric difference in AOD	0·1 (mean annual interhemispheric difference)	0·076 AOD	>80% of NH_3 emissions forming $PM_{2·5}$ (northern hemisphere); >50% of $PM_{2·5}$ emissions from biomass burning (southern hemisphere)	<20 Tg NH_3 (northern hemisphere); halting biomass burning emissions from land conversion (southern hemisphere)
Novel entities				
Percentage of synthetic chemical released to the environment without adequate safety testing[202,203]	0%	Transgressed	3·3–3·7 Tg PAS application per year (85–90% of total pesticide use); 73–130 kilotons of antimicrobial use in animals per year (73% of total antimicrobial use)	1 Tg PAS application per year to avoid high pollution risk; 0·2 Tg PAS application per year to remain below low pollution risk; halting prophylactic use; restricting antimicrobial use to a maximum of 36 000–75 000 tons per year

Food system pressures and food system boundaries are defined in te Wierik et al (2025).[16] The planetary boundaries control variables are mainly based on work by Richardson and colleagues,[14] except if indicated otherwise. AOD=aerosol optical depth. CO_2e=CO_2 equivalent. DU=Dobson unit. HANPP=human appropriation of net primary production. NPP=net primary production. PAS=pesticide active substances. $PM_{2·5}$=particulate matter with a diameter of <2·5 μm.

Table 2: **Earth system processes (and their control variables), planetary boundaries, current state, current food system pressures (with their relative contribution in parentheses), and the proposed food system boundary for multiple control variables**

Meeting rising food demands must be achieved with less land, and with food production methods that generate—rather than degrade—ecological functions.[204,205] Sustainable intensification entails achieving important reductions in environmental impacts through increased efficiency, reduced losses, and reduced pollution.[206] Ecological intensification, a subset of sustainable intensification, enhances the environmental performance of food production by promoting ecological processes within agricultural fields, farms, and landscapes, such as above-ground and below-ground carbon sequestration, nutrient cycling and storage, pollination, and biological pest regulation.[207,208] Here, we synthesise evidence on the impacts of key groups of practices for sustainable and ecological intensification (SEI) across field-scale indicators, to assess the potential of SEI in mitigating planetary boundary transgressions. We also use a novel ecological intensification module from the Food, Agriculture, Biodiversity, Land-use and Energy Calculator model[209] to assess the global potential of these practices across planetary boundaries (see section Reducing the environmental footprint of food production).

Climate change

Our food systems release almost a third of the emissions driving climate change, and are also especially vulnerable to global warming, which has profound effects on people's food supply and health.[210] Agricultural and food systems release 16–17·7 Gt of CO_2 equivalent (CO_2e) per year, or about 30% of total global greenhouse gas (GHG) emissions.[210–212] Around a third of these emissions come from agriculture, including both livestock and crop production, a third from conversion of natural ecosystems to cropping and grazing lands, and a third from non-agricultural aspects of food supply, including transport, cold storage, processing, retail, catering, food management in the home, manufacturing fertilisers and other agricultural inputs, and waste management (appendix 2 p 6).[210,212] Most agricultural emissions come from production of animal-sourced food (see section 4). Enteric fermentation from ruminant animals (ie, cows, sheep, and goats) and manure management linked to the meat and poultry industry account for large shares of these emissions (figure 3). Ruminant farming is the primary driver of land-use change.[208] Up to a third of emissions from food systems derive from off-farm food-related processes, including fertiliser production and distribution, post-farm food processing and transformation, and transportation. For example, more than 10% (1·9 Gt CO_2e per year) of global food system emissions are attributed to food that is lost or wasted along the supply chain.[213] Reaffirming the boundary set in the 2019 Commission, we propose that GHG emissions from food systems are kept below 5 Gt CO_2e per year by 2050 to keep global warming below 1·5°C or 2°C (figure 3). Several analyses support the boundary of 5 Gt CO_2e per year, highlighting that a more ambitious boundary is possible when mitigation options include dietary change (ie, to the PHD; appendix 2 p 7). The residual emissions in this food system boundary (ie, methane [CH_4] and nitrous oxide [N_2O]) arise from biological processes in agriculture, and are difficult to abate even with global adoption of the PHD. However, this boundary could theoretically be further reduced with

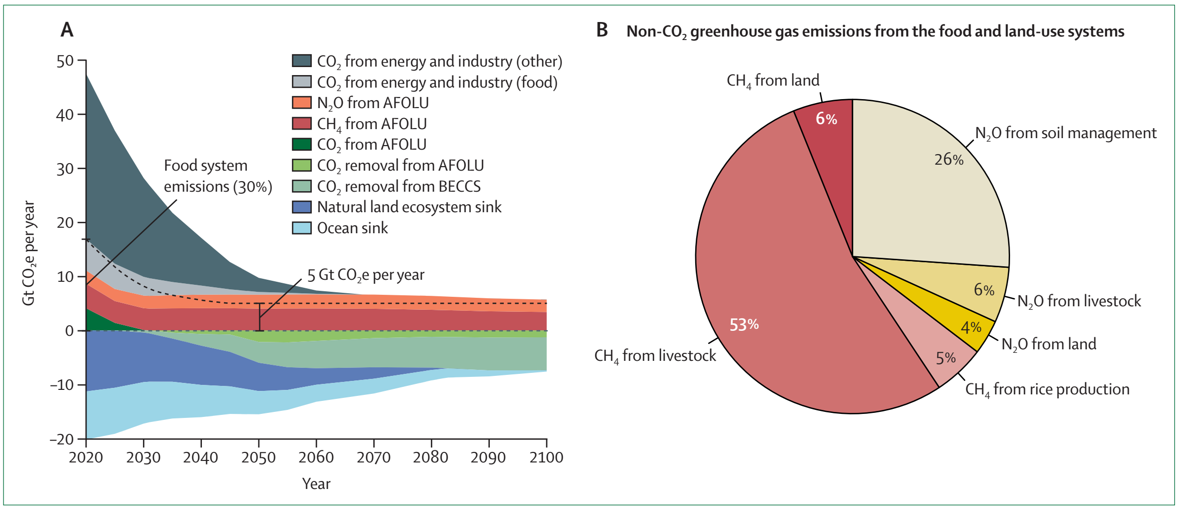


Figure 3: **Emission pathways to 1·5°C and food systems shares**
(A) Projections of global greenhouse gas emission reductions from AFOLU (ie, CO_2, CH_4, and N_2O) and energy and industry (ie, CO_2), including negative AFOLU CO_2 emissions and carbon sequestration from BECSS (Bioenergy with Carbon Capture and Storage) required to limit global warming to 1·5°C, with no or limited overshoot (C1). The dashed line shows this Commission's trajectory of the food systems' share of the safe operating space for climate; the food system boundary amounting to 5 Gt CO_2e per year consists of minimised flows of CH_4 and N_2O. Data are from the IPCC's sixth assessment report following selected scenarios (n=62) within the C1 category.[210] Additional carbon sequestration measures (eg, carbon capture and storage from fossil fuel use and industry, not depicted here) are necessary to remain within the 1·5°C limit. (B) Non-CO_2 emissions (ie, CH_4 and N_2O) from AFOLU in 2020. AFOLU=agriculture, forestry, and other land use. BECCS=bioenergy with carbon capture and storage. CO_2=carbon dioxide. CO_2e=CO_2 equivalent. CH_4=methane. N_2O=nitrous oxide.

wider adoption of increasingly plant-rich diets or major advances in emission-reducing technologies.

Unprecedented ambition is required to return to the safe operating space within the climate boundary. Full energy decarbonisation and zero land-use change would eliminate two-thirds of food system emissions by largely eradicating CO_2 emissions. Energy use would need to be decarbonised throughout the food system, including in food transport, refrigeration, and preparation; on-farm machinery; and manufacture of agricultural inputs. Achieving net-zero land-use change to align with land system change and biosphere integrity boundaries requires secure land governance, increased productivity, and reduced demand. The remaining third of emissions—the residual CH_4 and N_2O emissions from agriculture—can be reduced through dietary change, management of food waste, and better farming practices (eg, improved livestock feed and fertiliser-use efficiency). A further opportunity to keep food systems within the boundary is carbon sequestration in agriculture, which, when coupled with emissions reductions, could make food systems a net carbon sink (see section Reducing the environmental footprint of food production) by removing 1·4–5·5 Gt CO_2e per year (estimated economic potential at a carbon price of $100 per tonne).[210,214,215] SEI practices that sequester carbon include soil carbon management (removing 0·4–0·9 Gt CO_2e per year) and agroforestry (removing 0·4–1·1 Gt CO_2e per year), with soil carbon prices of $100 per tonne.

A systems approach is essential to navigate trade-offs between and rebound effects of alternative land uses. Options to reduce emissions diminish as our remaining carbon budget falls below 200 Gt CO_2e, making direct capture of emissions a universal component of scientific pathways to keep global warming below 1·5°C or 2°C (figure 3). Bioenergy with carbon capture and storage is often suggested as the preferred solution; however, this is a land-intensive solution that would compete with reforestation and afforestation and offset reduced demand for land to feed livestock.[216]

Land system change

Human activities have substantially altered the Earth's surface through conversion of intact lands to croplands, grazing lands, and other industrial and urban land uses. Approximately 50% of ice-free lands can still be considered largely intact (ie, natural ecosystems with low human appropriation or use).[36] Halting further conversion of these lands, with particular emphasis on protecting large forest biomes, is necessary to halt biodiversity loss, reduce human climate forcing, and secure hydrological functioning of ecosystems.[14,36,217] We set the land boundary at 85% intactness of ecoregions included in boreal and tropical forest biomes, and at 50–60% intactness for all other ecoregions as defined in the Planetary Boundaries and Earth Commission.[39] These levels are required to mitigate the impacts of climate change, and to halt the loss of biodiversity.

Currently, 48 M per km² (37% of the global land area) is used for agricultural production, of which croplands cover 33% and grazing lands cover 67%.[218] Almost 70% of ecoregions fall below the 50% intactness boundary,[36] predominantly driven by historical conversion of intact nature to agriculture (appendix 2 p 8). Agricultural land alone breaches the local intactness boundary (>50% agricultural land cover) in a third of ecoregions (appendix 2 p 9). The continuing loss of intact ecosystems, notably forests, is predominantly driven by agriculture[219] and is particularly high in tropical forests that are cleared for pasture, oil crops, and soy production.[219,220]

Remaining within the land system boundary requires zero conversion of intact lands, by keeping global agricultural area well below 48 M per km². This value is a modification of how the land boundary was articulated in the 2019 EAT–*Lancet* Commission (ie, land use for crops being kept at or below 13 M per km²). In addition to halting conversion, reducing agricultural land and restoring intactness is essential across ecoregions. This restoration is particularly important in forest biomes, which are strongly transgressed and require 5·5 M per km² of tropical forest restoration and 3 M per km² of temperate forest restoration, at the expense of agricultural land (appendix 2 p 9).

The key strategy to reduce agricultural land area is a shift to healthy diets, particularly away from animal-based products and associated feed production.[221,222] Decreasing food loss and waste is a catalyst for further reducing demand-side pressure. In summary, maintaining or increasing yields is essential for keeping agriculture within a reduced land area, recognising regional differences depending on their current yield levels. SEI practices chiefly show either improved (desirable effect sizes) or maintained (negligible effect sizes) productivity. Ecological intensification would require slightly more land than other practices aiming to improve production, but would still fall below the land boundary globally (see section Reducing the environmental footprint of food production).

Biosphere integrity

Life on our planet depends on the capacity of the biosphere to safeguard critical Earth system functions, which in turn requires healthy, functioning ecosystems. Two complementary control variables for biosphere integrity are biosphere functional integrity and ecosystem functional integrity. Biosphere functional integrity refers to the sum of net primary productivity (NPP) from all ecosystems on Earth and is therefore used as a control variable for the Earth system. NPP captures photosynthetic energy and material flows into the biosphere, with a deviation between potential NPP of intact ecosystems and the actual NPP of converted systems. The biosphere integrity boundary limits human appropriation of NPP (HANPP) to less than 10% of the Holocene NPP (5·5 Gt of carbon per year).[14] Ecosystem functional integrity refers to ecosystems' capacity to sustain nature's contributions to people (eg, food production).[223] Intact ecosystems have high functional integrity. This boundary, which is set at 20–25% of natural or semi-natural habitat per km², is therefore applied to agricultural and urban land-use systems. From an Earth-system perspective, functional integrity helps to maintain gene and species flow within and between ecosystems, reducing the risk of species extinctions when complemented with the land boundary described earlier. The 2019 EAT–*Lancet* Commission used a 10% boundary, citing a loss of ecosystem services for food production when this threshold is crossed. Reviews published in the past 5 years have increased this threshold, stating a boundary of 20–25% is necessary to maintain minimal functioning.[223,224]

Agricultural systems, particularly extensive monocultures, are the single largest drivers of both biosphere and ecosystem functional integrity loss, through reducing actual NPP from land conversion, extracting NPP by harvesting biomass, and below-threshold retention of habitat within agricultural lands. Agriculture is responsible for appropriating 72–85% of the total HANPP (9·9–11·7 Gt of carbon per year);[225] furthermore, 33–66% of agricultural land falls below the functional integrity threshold, and 88% of agricultural land is used for food and animal feed production (figure 4A).[222,223]

Remaining within the food system boundary for biosphere integrity requires a reduction of HANPP to within the safe planetary boundary threshold (<5·5 Gt of carbon per year).[16] This reduction can be achieved by increasing productivity on existing cropland (eg, by closing agricultural yield gaps from nutrient deficits), and restoring ecosystems on former agricultural lands (eg, reforestation), to increase actual NPP back to levels of potential NPP. Ecological intensification practices, although not directly assessed against HANPP here,

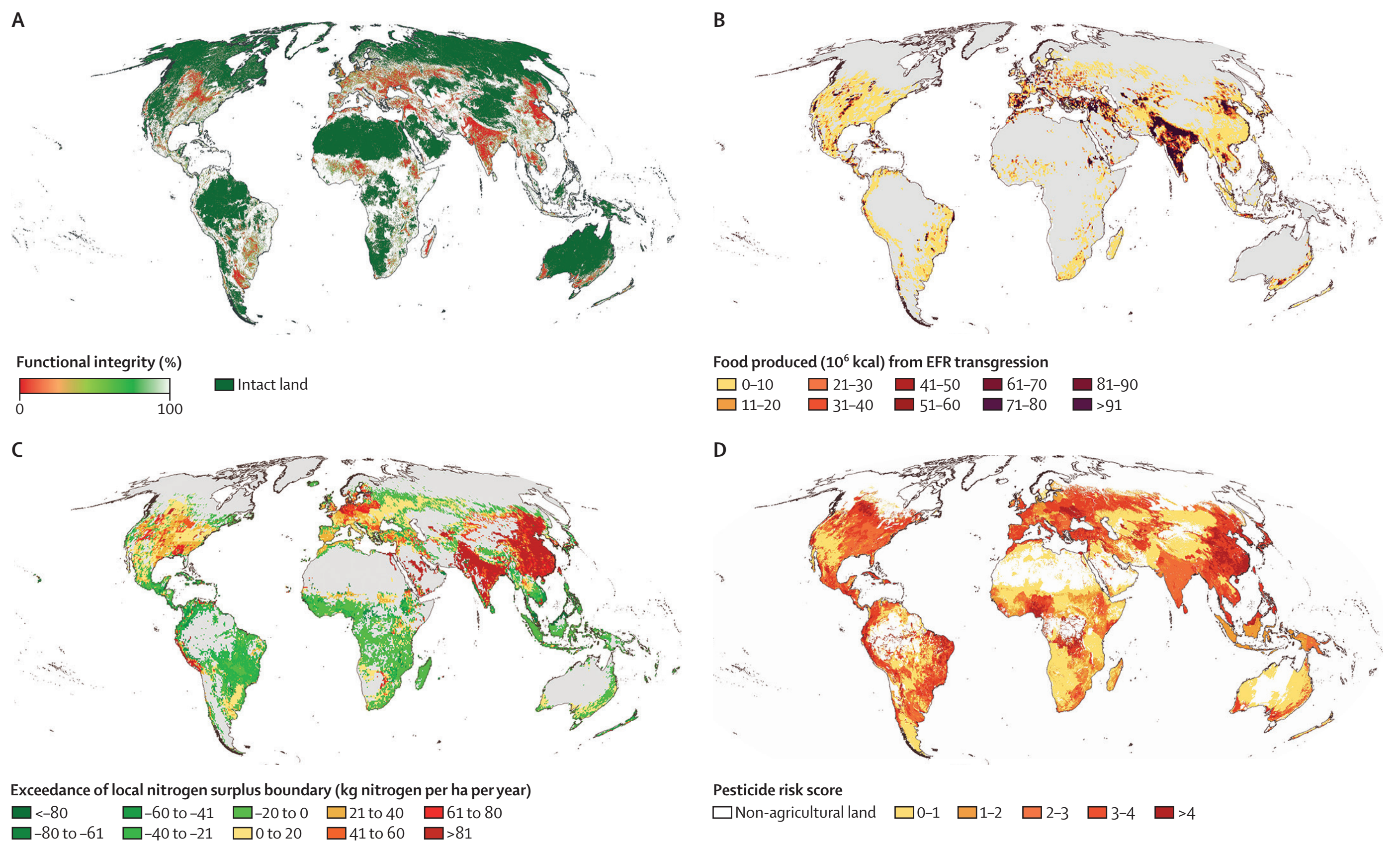


***Figure 4:* Present-day status of planetary boundaries for land, biodiversity, water, nitrogen, and pesticide use**

(A) Intact land (dark green) based on data from Rockström et al[39] and ecosystem functional integrity of existing agricultural land based on data from Mohamed et al.[223] (B) Blue water, with regions where irrigation use exceeds freshwater EFRs, expressed as kilocalories of food produced per year from water that violates EFRs. Restricting irrigation without compensatory measures can affect yields in half of irrigated croplands (data from Jägermeyr et al[226] and Gerten et al[227]). (C) Regions where the local nitrogen boundary is exceeded (values >0), and regions where nitrogen surplus boundaries are not yet exceeded and allow for an increase in nitrogen to meet crop demand (kg nitrogen per hectare per year; data from Schulte-Uebbing et al[51]). (D) Pesticide risk scores, indicating the exposure of agricultural land to pesticide pollution, are classified following average species sensitivity curves: low risk (0–1), medium risk (2–3), or high risk (>3). Data from Tang et al.[52] Grey areas indicate no data. EFRs=ecosystem flow requirements.

include practices to ensure that larger portions of NPP are retained in or returned to fields (eg, as crop residue, manure, or perennial vegetation). Maximum field-scale HANPP of sustainable production systems is not reviewed here but merits attention as a key scalable sustainability metric to include in sustainability assessments. Reducing HANPP from harvested crops (currently ±2 Gt of carbon per year)[225] is only possible through dietary shifts that reduce HANPP from crop production for animal feed, and by reducing food loss and waste and feeding losses. Globally, around 775 kcal per capita per day is lost or wasted (representing approximately 20% of agricultural land use), of which the majority are crops. These losses occur along the entire supply chain (ie, post harvest, retail, food service, and households).[213,228]

Increasing the functional integrity of agricultural lands requires widespread inclusion of embedded habitats to return within the safe space of the planetary boundary.[223,224] This target can be achieved by context-specific practices, including protecting and restoring riparian buffers and hedgerows, improved fallows, and returning crop waste to fields. Furthermore, agricultural diversification practices support ecosystem functional integrity directly and can be managed to further enhance carbon sequestration through above-ground and below-ground carbon capture (climate boundary); increase biological pest control and pollination, thus reducing dependency on biocides (novel entities boundary); and reduce losses of nutrients to the environment by capturing and storing nutrients before they are lost to waterways (biogeochemical flows boundary).

Freshwater change

Freshwater availability is essential to support drinking water needs, ecosystem functioning, and climate mitigation by enabling carbon sequestration in the biosphere.[229] The freshwater cycle is increasingly altered by human actions, affecting both blue water (eg, rivers, reservoirs, and groundwater) and green water (held in soil and in plants).[230] Recent planetary boundary assessments show that we have transgressed boundaries for both blue and green water.[14,231] These boundaries propose limits to the occurrence of exceptionally dry and wet local events (including blue and green water availability), and deviate from the blue water boundary proposed in the 2019 Commission, which is based on volumetric limits for consumptive water use. The 2019 Commission constrained global agricultural consumptive use to less than 2500 km³ per year[232] to preserve regional ecosystem flow requirements (ie, the minimum volume, timing, and quality of water flow needed to maintain good ecological status of aquatic systems). Here, we adopt the novel boundary definition for green water (ie, the global land area that is within the local variability baseline for soil moisture), while keeping—although updating—the volumetric limit for blue water.

Food systems are major users of blue water, mainly via irrigation.[16,233] Water withdrawal estimates from rivers and groundwater range between 2700 and 3100 km³ per year,[211,233] of which 1200–1800 km³ per year is for consumptive use.[233,234] Irrigation is responsible for around 70–90% of global consumptive water use, although estimates vary depending on the methods and models used.[16,234] The majority of agricultural land and production is directly irrigated from rainfall[16] and therefore depends solely on green water,[233] but soil moisture availability is changing across the world,[231] including on agricultural lands (16·8% of agricultural land currently transgresses the green water boundary).[235] We preliminarily define the food system boundary for green water based on the latest planetary boundary definition (ie, limiting the land area beyond pre-industrial variability baseline to 11%).[16] For blue water, we propose that agricultural water consumption remains below 2000 km³ per year, which is lower than in the 2019 Commission (ie, 2500 km³ per year), which allocated 90% of the boundary's safe operating space to agriculture. We propose a more stringent approach given the uncertainties around agricultural consumptive water use,[233] and acknowledge the lower—and stricter—end of the planetary boundary's uncertainty range (1100 km³ per year).[232] Although this proposal suggests that food systems worldwide are within the freshwater planetary boundary (table 2), many rivers are experiencing severe water stress from irrigation water withdrawal alone.[226] In fact, more than 5% of global food production depends on transgressing regional blue water boundaries by drawing on ecosystem flow requirements (figure 4B).[226] In these areas, lowering demand for irrigation water without affecting crop yields could be achieved by growing foods with lower water demands,[236] reducing food loss and waste (as 20% of freshwater withdrawals are currently wasted),[211,213] and increasing water productivity through the adoption of agricultural practices that improve soil water-holding capacity. SEI practices are effective in increasing soil organic carbon content, which in turn improves the water-holding capacity of soils.[237] Crop and non-crop diversification, especially agroforestry,[238] shows strong desirable effects on the water regulation of soils (eg, by creating a diverse rooting system with different species, rooting profiles, and depths).

Biogeochemical flows: nitrogen and phosphorus losses

Nitrogen and phosphorus have important roles in crop and pasture production. In some regions, crop yields are below their potential due to insufficient nitrogen and phosphorus availability; in other regions, surplus agricultural nitrogen and phoshorus from excessive nutrient inputs causes environmental pollution, leading to biodiversity loss and effects on human health, such as methemoglobinaemia, colorectal cancer, thyroid disease, and birth defects (panel 2).[50,201] In addition, N_2O emissions from fertiliser and manure contribute to climate change and stratospheric ozone depletion. Here, we use nitrogen surplus from agricultural land as a control variable (defined as nitrogen input minus nitrogen removal via crops and grass).[151] In contrast to the nitrogen input variable used in the 2019 Commission, nitrogen surplus accounts for the remaining reactive nitrogen that can lead to environmental harm via deposition on natural ecosystems, groundwater leaching, and surface water load.

Unlike nitrogen input estimates, nitrogen surplus estimates are unaffected by nitrogen use efficiencies (NUE; nitrogen removal from plants compared with total nitrogen input), and do not include nitrogen removed from plants, which can move up the food supply chain and enter the environment via wastewater streams (eg, via human excreta). The planetary boundary for nitrogen surplus on agricultural land is 57 Tg of nitrogen per year, allowing for increased nitrogen use in regions that are currently deficient (figure 4C).

For our phosphorus variable, we adopt the concept of phosphorus losses to surface water, which strongly depends on available phosphorus stocks in soil and rates of erosion. Because applied (ie, excess) phosphorus can be adsorbed and can increase phosphorus stocks without directly harming the environment (unlike nitrogen), we use the amount of phosphorus lost to surface water as our control variable, rather than applied phosphorus (as in the 2019 Commission). On the basis of phosphorus concentrations needed to preserve the ecological status of global surface waters,[239,240] we propose a global boundary for phosphorus loss of 6·1 Tg per year.[241]

Current agricultural nitrogen inputs on cropland and managed grasslands (233 Tg of nitrogen per year) are partly removed by crops (114 Tg per year), while 119 Tg per year remains as surplus.[51] This surplus—together with other sources of nitrogen from wastewater, aquaculture, nitrogen oxide deposition from transport, and natural sources (ie, allochthonous matter)—contributes to nitrogen deposition on terrestrial ecosystems (23 Tg per year; around 50% from food systems), nitrogen loading in surface water (71 Tg per year; around 70% from food systems), and leaching to ground water (56 Tg per year; around 80% from food systems; appendix 2 p 10).[16,241] Furthermore, almost 10 Tg of phosphorus per year is delivered from soils to surface water, with 72% of the phosphorus delivery (7·2 Tg per year) being derived from food systems (appendix 2 p 10).[201]

Based on current NUE, bringing surplus agricultural nitrogen back within global safe levels (<57 Tg per year) requires a reduction of agricultural nitrogen input from 233 to 134 Tg per year (panel 4; figure 5).[51] Assuming proportional reductions across other sectors only slightly relaxes this value (to 140 Tg of nitrogen per year),[51] as most sources of nitrogen are attributed to food systems (eg, agriculture, aquaculture, and from waste water; appendix 2 p 10). Further reducing the contribution from natural nitrogen sources (ie, from allochthonous organic matter) is not possible. We therefore propose the food system boundary for surplus nitrogen be equal to the planetary boundary.

Increasing NUE from 0·48 (the current global average) to an achievable 0·67[244] could bring us close to the safe operating space without compromising yield.[51] Nutrient surpluses (ie, nutrients not taken up by plants) are unevenly distributed globally; as such, nitrogen redistribution is as important as reducing fertilisation rates in limiting harmful environmental effects (figure 4C).

Agricultural diversification and nutrient management (eg, the right type, amount, rate timing, and placement

Panel 4: Circular food systems

Transitioning to more circular food systems is thought to potentially reduce mineral nitrogen and phosphorus use. To assess these potential contributions, we used CiFoS,[242] a biophysical optimisation model, to simulate four 2050 scenarios that were benchmarked to a 2020 simulation (more details in appendix 2 pp 20–21).[243]
The four scenarios were:

- The BAU-Opt scenario optimises a future 2050 scenario by minimising multiple environmental impacts of the food systems' share of planetary boundaries (ie, greenhouse gas emissions, land use, and nitrogen and phosphorus use) by reallocating production globally. The economic and social implications of this reallocation were not assessed.
- The BAU-Opt+Cir scenario allows for a transition to a more circular food system in which leftovers (eg, by-products, human excreta, feeding losses, and food loss and waste) are recycled.
- EL-Opt simulates a scenario that allows for dietary shifts compatible with the planetary health diet, food loss and waste reductions of 50%, and production increases (in line with the multimodel ensemble described in section 4).
- The EL-Opt+Cir scenario adds circularity components to EL-Opt.

In the BAU-Opt scenario, the production of leftovers was lower (4·1 Gt per year) compared with BAU-Opt+Cir (6·8 Gt per year) and the difference between EL-Opt (1·7 Gt per year) and EL-Opt+Cir (3·1 Gt per year). The use of leftovers increased from 24% in BAU-Opt to 84% for BAU-Opt+Cir, and from 22% in EL-Opt to 90% for EL-Opt+Cir (figure 5A). Results in the circular scenarios (ie, BAU-Opt+Cir and EL-Opt+Cir) show a preference for recycling over reducing the production of leftovers. In 2020, 259 Tg of nitrogen and 40 Tg of phosphorus are used, including from both mineral fertilisers and organic sources (figure 5B). In an optimised—but not circular—food system (BAU-Opt), nitrogen use decreased by 21% in 2050 (to 205 Tg per year) compared with 2020 values, and phosphorus use decreased by 49% to 21 Tg per year. Adding circularity measures (ie, BAU-Opt+Cir) reduced nitrogen use by 29% to 184 Tg per year, and phosphorus by 55% to 18 Tg per year, whereas the EL-Opt scenario reduced nitrogen use by 45% to 142 Tg per year, and phosphorus by 67% to 13 Tg per year. Combining circularity with a food system aligned with the EAT–*Lancet* scenario (ie, EL-Opt+Cir) reduced nitrogen use by 50% to 128 Tg per year and phosphorus use by 73% to 11 Tg per year. In both the EL-Opt and EL-Opt+Circ scenarios, nitrogen use and phosphorus use are projected to stay largely in line with their respective planetary boundaries (ie, 134 Tg of nitrogen per year to stay within the yearly surplus boundary of 57 Tg [table 2], and between 8 and 16 Tg of mineral phosphorus fertiliser per year[234] to limit the amount of phosphorus reaching surface waters). Although results of the EL-Opt and EL-Opt+Cir scenarios only differ slightly, clear differences exist between the fertiliser sources used (ie, more organic fertiliser sources are used in the EL-Opt+Cir scenario; figure 5B). Nevertheless, despite substantial reductions in mineral fertiliser use due to increased circular sources of nitrogen and phosphorus (in the El-Opt+Cir scenario), mineral fertilisers remain an important input in agricultural production.

of fertiliser) can reduce nutrient losses to the environment and improve NUE, with some increased—and chiefly neutral—yield effects. Although reduced soil disturbance (eg, conservation tillage) showed mixed results for minimising nutrient losses, no-till farming reduces phosphorus losses.[244,245] Soil phosphorus stocks below target levels should be increased globally, and phosphorus application should maintain this increase by replacing removed phosphorus during cultivation and harvest, and by reducing soil erosion.

Keeping nitrogen and phosphorus within boundary conditions remains a challenge if greater attention is not given to food system losses arising from food consumption. Recovery of nitrogen and phoshorus sources from sewage water should also be implemented to prevent post-consumption losses, as around 12 Tg of nitrogen per year from human excreta is lost to surface waters.[201] The effect of circular systems on staying within the planetary boundary remains poorly assessed (but see panel 4) and merits attention. Recycling nitrogen and phosphorus in fields, not only with manure but also with compost and sludge, decreases losses to the biosphere; however, these practices are increasingly challenged by novel entity contaminants (eg, so-called forever chemicals) in organic waste streams, which can make agricultural fields toxic.[246]

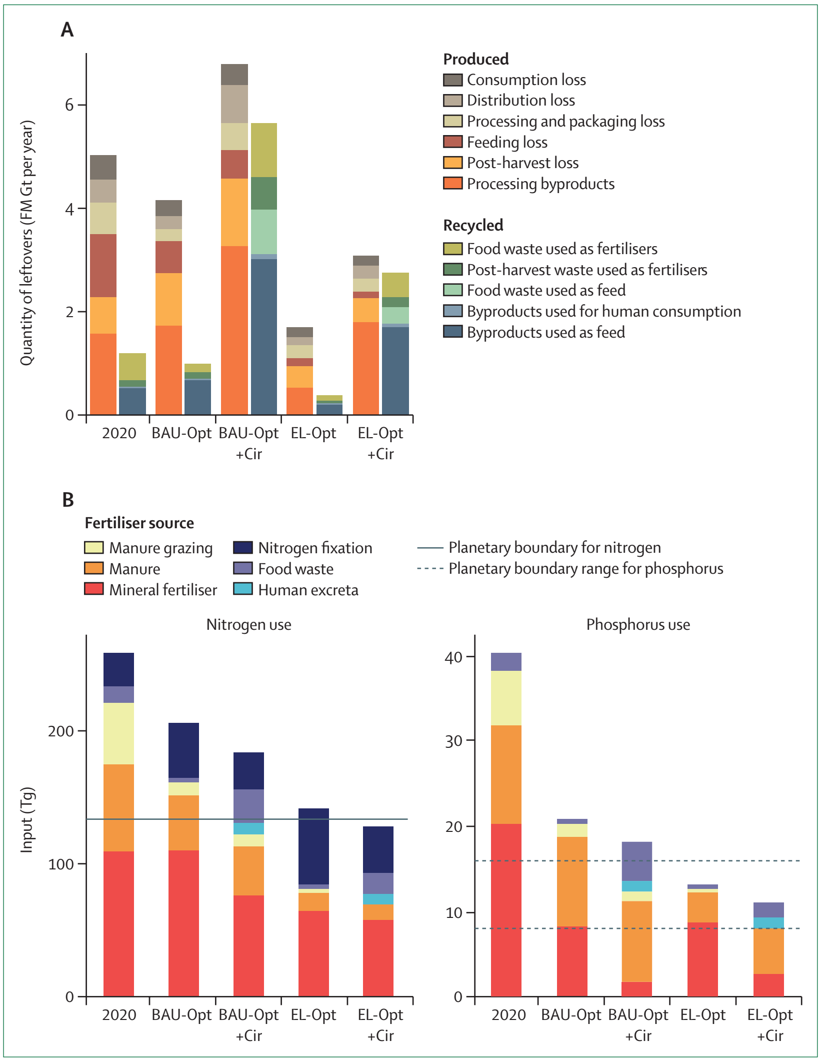


Figure 5: **Effect of circularity on use of leftovers and biogeochemical cycles on a global food system level**
(A) Total leftovers and recycled leftovers per scenario in Gt fresh matter per year. The left bars show total byproducts and food loss and waste (ie, leftovers), categorised into post-harvest, processing, distribution, feeding, and consumption losses. The right bars show the recycled or repurposed share of food loss and waste and byproducts used as fertiliser, human food, or animal feed. (B) Nitrogen and phosphorus input to agricultural land across scenarios, categorised by fertiliser source (ie, mineral and organic). FM=fresh matter.

Novel entities

The planetary boundary for novel entities proposes limits to the release of human-made substances in the environment, ranging from synthetic chemicals (eg, plastics and endocrine disruptors), to radioactive materials and genetically modified organisms. The risk posed to Earth system stability and resilience from novel entities is uncertain; however, their cumulatve effects (eg, from chemical interactions of multiple substances in the environment) are potentially large, persistent, and life threatening. More than 350 000 synthetic chemicals are produced and released in the environment, and many are insufficiently tested for their potential environmental risks.[247] Uncertainties regarding the associated risks of novel entities continue to obfuscate the definition of a novel entities boundary, which precautionarily restricts the release of any synthetic chemical compound that has not been adequately tested to show that no harmful environmental effects occur upon its release.[14,247]

Although novel entities were not assessed in the 2019 Commission, pesticides,[52,202] genetically modified crops, antimicrobials, plastics and microplastics,[248] and so-called forever chemicals (eg, perfluoroalkyl and polyfluoroalkyl substances) are all released and used within food systems.[249] Here, we adopt pesticide application and antimicrobial use as indicators for novel entities, because of their widespread use in agriculture and potential risks to the environment and human health.[16,250,251]

Pesticides are widely used in crop protection and weed control and pose major health risks to non-target species. Global pesticide application amounts to 3·3–3·7 Tg of pesticide active substances per year,[250] of which 85–90% is used in agriculture.[252] Safety levels for individual pesticide concentrations are exceeded throughout terrestrial and aquatic systems (figure 4D). Although most pesticides degrade over time, remaining residues build up in organisms and pose risks through mixing effects in the environment.[253] Furthermore, legacy contamination can continue for extended periods of time (sometimes decades) in soil, surface water, and ground water.[202] These factors challenge the definition of safe levels of pesticide use. To minimise the exceedance of high environmental risk (ie, >90% probability of a random species being affected by pesticides), we propose a 70% global reduction in pesticide application, equating to a maximum of 1 Tg of pesticide active substances per year (appendix 2 p 11). A further reduction of more than 95% (ie, maximum application of 0·2 Tg of pesticide active substances per year) is required to ensure low environmental risk (ie, <5% probability of a random species being affected by pesticides).[16,52]

Ecological intensification practices can manage pest outbreaks without compromising crop yield, while also enhancing biosphere functional integrity.[254] However, some agricultural practices, such as reduced soil disturbance, can result in higher weed loads, highlighting the importance of using integrated complementary practices (see section Reducing the environmental footprint of food production).

Antimicrobial use for livestock production is estimated at 73–130 kilotons per year[203,255,256] and has increased antimicrobial resistance prevalence.[111] Setting a boundary for antimicrobial use is challenging due to uncertainties in the environmental risks of increasing antimicrobial resistance.[251] Based on WHO recommendations and available evidence on reducing average application rates but keeping effective production systems,[256] we propose completely halting prophylactic antimicrobial use, and halving existing average application rates from 50 to 25 mg/kg per animal.[16] Global shifts to flexitarian diets can reduce global antimicrobial use by around 42% compared with baseline values for 2050; combining this shift with moderate biosecurity measures (eg, handwashing, preventing bites, and wearing protective clothing) could reduce global use by 49%.[65]

Aerosol loading

Air pollution is a major human health issue (panel 2), negatively affects crop production by changing photosynthetically available light,[257] and can have major Earth system impacts on precipitation and circulation patterns of the atmosphere and ocean. The planetary boundary for aerosol loading is expressed as the mean annual interhemispheric difference in the aerosol optical depth,[14] capturing the reduction in sunlight from air pollutants, such as nitrogen components (eg, ammonia [NH_3], nitrogen oxides, and N_2O), sulphur dioxide, carbon monoxide, organic compounds, and particulate matter. An increased aerosol optical depth affects regional rainfall patterns, and changes in interhemispheric difference are associated with abrupt transitions in monsoon systems. Although the planetary boundary for atmospheric aerosol loading has not been transgressed (table 2), food systems are a prominent source of air pollutants (appendix 2 p 11), such as ammonia from fertiliser use and livestock production (37–47 Tg nitrogen per year; 86% of total NH_3 emissions);[51,258] airborne dust from human-driven land system change (eg, desertification and land management practices); and primary emissions of particulate matter with a diameter less than 2·5 μm ($PM_{2·5}$; >28% of total primary $PM_{2·5}$ emissions), mostly from burning for clearing vegetation.[258] Dominant sources of emissions vary regionally and between hemispheres.[47] In parts of the northern hemisphere, nitrogen-based emissions from livestock and fertiliser are the dominant source of aerosol loading, accounting for more than 80% of NH_3 emissions forming secondary $PM_{2·5}$ particles, and in the southern hemisphere, biomass burning is the predominant source of trace-gas emissions and $PM_{2·5}$ concentrations.[47] Emissions from biomass burning (globally estimated to contribute 42 Tg of $PM_{2·5}$ per year)[259] that can be attributed to agriculture are difficult to quantify, although some estimates suggest that 28% of direct $PM_{2·5}$ emissions worldwide are food-related (appendix 2 pp 3–5). Shares of emissions can vary between regions, particularly in the southern hemisphere (ie, biomass burning is responsible for 90% of $PM_{2·5}$ emissions in Angola).[47]

Remaining within aerosol boundaries requires emission reductions in both the northern and southern hemisphere. The boundary for nitrogen surplus suggests a reduction of NH_3 emissions is required (>45% reduction of current emissions, from 37 to 20 Tg of nitrogen per year). This reduction is most important in the northern hemisphere, where the nitrogen surplus (and associated NH_3 emissions from manure and fertiliser)[51] is high (figure 4C). Dietary shifts towards the PHD can reduce agricultural NH_3 emissions by more than 50% in North America and Europe.[48] In the southern hemisphere, biomass burning from land conversion and on agricultural lands should be eliminated, in line with the land system change and climate change boundaries. However, whether reducing NH_3 emissions and biomass burning can lower total $PM_{2·5}$ concentrations across hemispheres is unknown.[116]

Ocean acidification

Ocean acidification is linked to the loss of marine species dependent on calcium carbonate, and changes to marine carbon storage. Acidification also aggravates the effects of other biogeochemical changes (eg, ocean warming and its associated thermal heat stress), and is therefore considered to be a threat multiplier for marine life.[260] Ocean acidification, measured through the change in the aragonite saturation state (Ω_{arag}),[14] is driven by atmospheric CO_2 concentrations (as 25% of historical anthropogenic CO_2 emissions are absorbed by the ocean)[261] and is therefore strongly related to the climate boundary. Although the ocean acidification planetary boundary is not yet transgressed (table 2),[14] it is moving rapidly into the zone of increased risk given the near-constant CO_2 emissions (ie, 40·6 Gt of CO_2 per year, of which food systems are responsible for nearly 25%).[16,212] Remaining within the food system boundary for climate change and biosphere integrity can largely diminish CO_2 emissions (to near zero) and avoids transgressing the ocean acidification boundary.

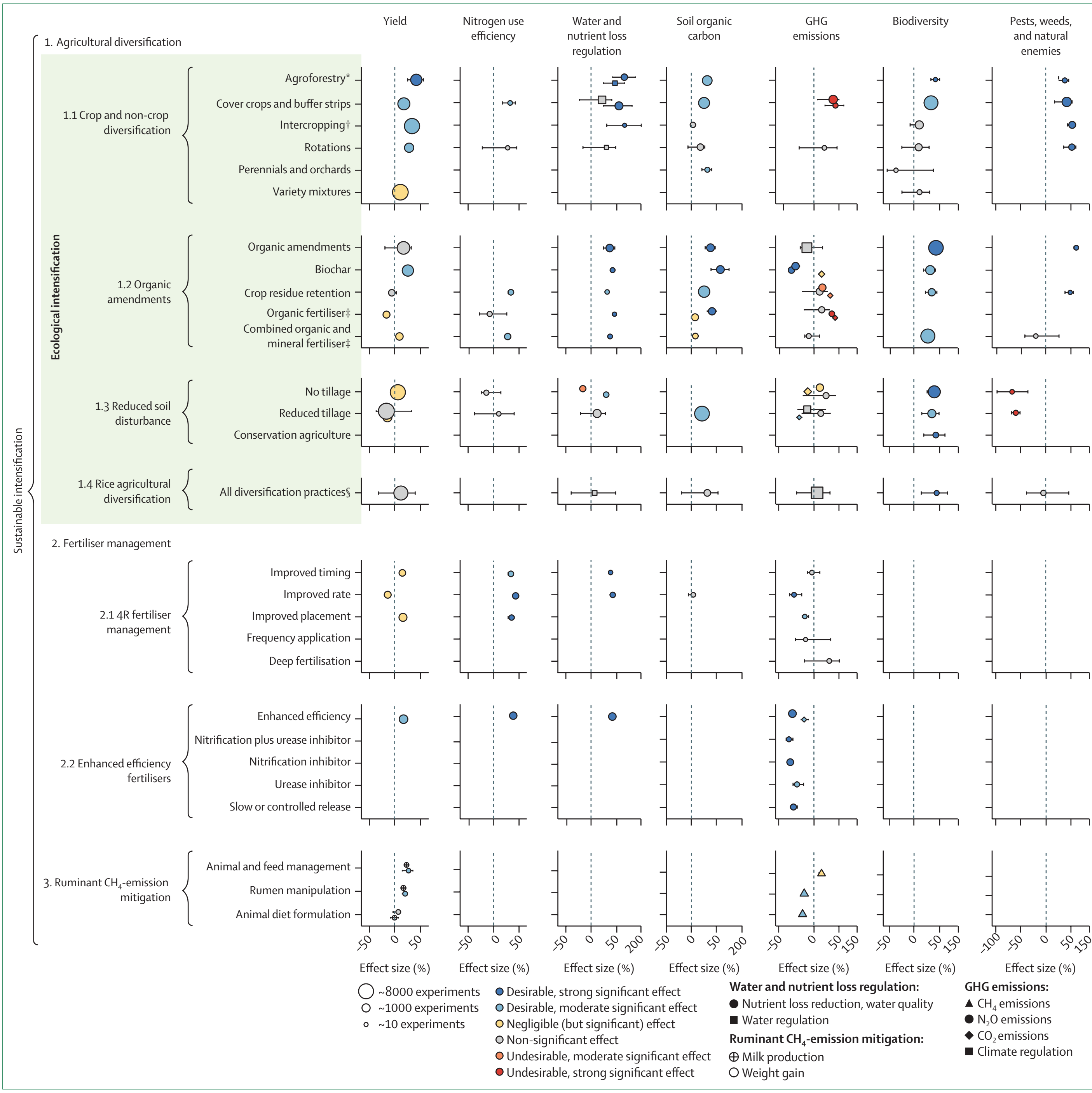


***Figure 6:* Relative contributions of sustainable and ecological intensification practices across field-scale planetary boundary indicators**

Rows indicate practices (eg, no tillage), organised into principles (eg, reduced disturbance) and further into groups (eg, agricultural diversification). Effect sizes represent the mean relative change when a practice is applied, in comparison to a conventional alternative or to the absence of applying the practice. Positive effect sizes are desirable for all indicators except greenhouse gas emissions, for which the desired effect is a reduction and hence negative. Symbol sizes represent the amount of experimental data used for calculating the effect size. Error bars show the 95% CIs for the mean effect sizes. When the CIs do not overlap with zero (ie, the dashed vertical lines), the effect is considered statistically significant. Missing values indicate no evidence found. The horizontal axis is square-root-transformed. Data used for the figure are available (appendix 3; see appendix 2 pp 15–17 for details on the planetary boundary indicators and the practice typology).[240,244,263–268] 4R=right type, right amount, right timing, and right placement of fertiliser. CH_4=methane. CO_2=carbon dioxide. GHG=greenhouse gas. N_2O=nitrous oxide. *Includes silvopastures. †Includes grass production, land-equivalent-ratios (LERs), and grain yields (the mean effect sizes for grain yield and LERs are positive on average, but non-significant). ‡For organic fertilisers and combined organic and mineral fertilisers, the control experiment is application of mineral fertiliser; for all other practices in the group, the control is no application of organic amendment, without further specification. §Includes rice–animal integration.

Stratospheric ozone depletion

The planetary boundary for stratospheric ozone depletion limits the breakdown of ozone that protects life on Earth from harmful solar radiation. Coordinated global interventions that have phased out production of ozone-depleting chlorofluorocarbons and halons (ie, through the Montreal Protocol adoption in 1987) have restored the ozone layer.[14] However, the most important ozone-depleting substance remaining is N_2O, which is not regulated under the Montreal Protocol. Agriculture is the largest emitter of anthropogenic N_2O (contributing to 54–69% of total N_2O emissions);[262] however, despite this contribution, ozone depletion rates remain insignificant. Even without reductions in N_2O emissions, stratospheric ozone levels are expected to recover by the end of this century.[51] We therefore restate the nitrogen surplus boundary, which adheres to local boundaries for biodiversity and water quality and thereby reduces N_2O emissions from fertiliser and manure applications by nearly 55% compared with current levels (ie, from 3·9 to 1·8 Tg of nitrogen per year).[16,51]

Reducing the environmental footprint of food production

SEI practices offer considerable potential to mitigate planetary boundary transgressions without negatively affecting yields (figure 6), and many offer cross-boundary benefits. Soil organic carbon accumulation can be enhanced with agricultural diversification practices that promote plant root formation, microbial activity, and the return of organic matter to soils, thereby reducing HANPP; however, uncertainties remain regarding the permanence of soil carbon pools, which challenge estimates of this potential.[269,270] Agricultural diversification increases agroecosystem biodiversity, which can be specifically managed to assist in weed and pest abatement, or to reduce the prevalence of crop diseases and nutrient losses while also maintaining or improving yields. Improved fertiliser management enhances crops' NUE, reduces nutrient losses, and contributes to soil organic carbon accumulation, albeit with increased variability in GHG emissions and yields.

The environmental effects of these practices (figure 6) are not directly additive, as they were typically obtained from studies comparing a single practice with a controlled alternative. Practice effects vary depending on context-specific, biophysical factors such as climatic and soil conditions, and the exact implementation of the practice. Working farms typically implement multiple practices simultaneously, and current evidence suggests synergies leading to enhanced environmental and social benefits.[271] Although meta-analyses provide valuable information on the technical potential of SEI practices at the field scale, estimates of the global potential of selected practice groups have also been explored in modelling studies (panels 4, 5, 6; table 3; figures 5, 6). These modelling studies, using different methods, factor in additional constraints and moderators of SEI practices. When applied to all suitable areas globally, and assuming maximum complementarity among measures, sets of SEI practices were found to provide a potential increase in NUE (from 48% [its average] to 78%)[244] and a global carbon sequestration potential between 0·44 and 0·68 Gt of carbon per year. When limitations of application and current application levels were factored in, the carbon sequestration potential was estimated to be 0·28–0·43 Gt of carbon per year,[215] and the GHG mitigation potential of around 4·4 Pg CO_2e was estimated to occur by 2050.[278] Despite these limitations, our synthesis shows substantial evidence that the evaluated, key groups of SEI practices can contribute to maintaining or improving yields and mitigating planetary boundary transgressions, based on the indicators considered (figure 6; appendix 2 pp 12–19). The potential global benefits of accelerating adoption of ecologically intensive practices on croplands vary across boundaries, but, in combination with other food system practices, these benefits have notable impacts on climate and biosphere integrity boundaries (panel 6).

See Online for appendix 3

Integrating livestock into food production systems, when respecting local environmental capacities (eg, nutrient loads and grazing intensities), can represent an SEI strategy that supports ecological processes in agricultural ecosystems (panel 7; figure 7).[298] Livestock can have an integral role in the food web, such as in nutrient and energy cycling, and can promote biodiversity. Furthermore, livestock and crop production practices can be interlinked via feed production, for both

Panel 5: Conservation agriculture—a combination of sustainable and ecological intensification practices with impact at scale

Conservation agriculture is a well established,[272,273] widely applicable and applied[274] example of the complementarity of sustainable and ecological intensification practices, whereby reduced soil disturbance, continuous soil cover, and crop diversification form the basis of the system. In this integrated approach, reduced soil disturbance protects the soil from erosion and conserves moisture, continuous cover suppresses weeds, and crop diversification reduce pests and disease. In our simulation scenario, conservation agriculture consists of no tillage, no crop residues left on fields, and the use of non-leguminous cover crops, which results in an estimated 22% decrease in nitrogen leaching, a 15% increase in root-zone soil moisture, and a 2% increase in soil organic carbon by 2050, when compared with a land-use scenario with no conservation agriculture (calculated as the average of two integrated assessment models and five global change models; appendix 2 pp 12–19). Other sustainable and ecological intensification practices can be combined with conservation agriculture. For example, in another simulation scenario, when rainwater harvesting was combined with conservation agriculture, global modelling results showed a minor added reduction for nitrogen leaching (2%) and a small increase in root-zone soil moisture (2%), but effectively no change for soil organic carbon. Although field studies have shown that the exact outcomes of conservation agriculture are context-specific, evidence shows that the farming system improves crop productivity, especially in dry climates and rain-fed production systems, therefore offering an adaptation strategy for climate change.[275,276] In resource-poor and vulnerable smallholder farming systems, socioeconomic challenges in the appropriate adoption of conservation agriculture should be carefully considered.[277]

terrestrial livestock and farmed fish, with synergies between practices gained through cover-crop grazing,[299] forage rotations, or integrating animals into weed or pest management.[300] In addition, grazing can affect levels of soil organic carbon in grasslands; evidence is variable[265] but suggests that less intensive grazing systems can enhance soil organic carbon.[301] Some of the practices assessed in this Commission (figure 6) include livestock integration (namely through silvopastoral systems), the use of manure as an organic amendment, and rice–animal co-cultures.

A comprehensive assessment of foods from aquatic systems is provided by the Blue Foods Assessment.[302] For wild fisheries, improved yields and environmental performance can be achieved by fishing within ecological limits, being informed by scientific advice,[303,304] and using production methods that limit indirect impacts to ecosystems (eg, habitat destruction and bycatch),[305] such as co-managing marine areas with local communities.[306,307] In aquaculture, most environmental impacts are driven by feeds[308] that emit GHG and are grown using croplands;[309] however, aquatic farms can also affect local ecosystems through acidification, eutrophication, and altering disease risks for wild populations.[310,311] These impacts can be reduced through SEI practices that improve nutrient cycling and feed efficiencies. For mariculture, integrated multitrophic systems, such as those growing bivalves and seaweeds near fish farms,

Panel 6: Initial estimates of environmental gains made through ecological intensification by the FABLE model

The Food, Agriculture, Biodiversity, Land-use and Energy (FABLE) Calculator is a demand-driven food and land-use system model designed to explore the food, biodiversity, climate, water, and socioeconomics impacts of future development pathways.[25] The model includes 88 agricultural products to show how their demand drives land-use change and the associated impacts on food and nutrition security, climate mitigation, biodiversity, and socioeconomic outcomes.

The FABLE Calculator differentiates between types of agricultural practices used on croplands and can therefore be used to explore the effect of scaling ecological intensification practices. Here, ecological intensification represents crop and non-crop diversification, including intercropping, cover crops, crop rotations, agroforestry, cultivar mixtures, and embedding natural vegetation into cropped landscapes. We modelled the effect of continuing current trends (with the business-as-usual [BAU] scenario) versus expanding ecological intensification practices across all croplands by 2050, in combination with the EAT–*Lancet* population growth, economic growth, climate change, diet, productivity, and food loss and waste assumptions as described in the modelling section and appendix 2 (p 22). The EAT–*Lancet* scenario—in which agricultural practices match BAU assumptions—represents a subportion of the EAT–*Lancet* and ecological intensification scenario, allowing us to isolate the effects of ecological intensification alone (appendix 2 pp 22–23).

The FABLE Calculator results (table 3) show that under the BAU scenario, food system boundaries for land, biodiversity, emissions, water, and nutrient use are exceeded by 2050. Under an EAT–*Lancet* scenario, the food system stays within land, biodiversity, and emission boundaries. Increased productivity, dietary shifts, and reduced food loss and waste reduce the land area needed for agricultural production, which drives the expansion of natural land available for biodiversity. Under the BAU scenario, annual net greenhouse gas emissions would fall from 7·35 Gt CO_2 equivalent (CO_2e) in 2050, to 2·75 Gt CO_2e under the EAT–*Lancet* scenario (ie, a ~60% reduction compared with 2020 values). This reduction in greenhouse gas emissions is greater than those suggested by the economic model ensemble (a median reduction of 20%), or by the Global Input–Output module of the Dietary Impact Assessment model (a reduction of 32%; see section 4), which could be explained by differences in how emissions are computed across models. Reduced greenhouse gas emissions in FABLE's EAT–*Lancet* pathway are driven by a decrease in emissions from agricultural production for both crops and livestock, and increased carbon sequestration from avoided deforestation and restoration of abandoned agricultural land to forest and other natural land (with higher rates of carbon sequestration in living biomass and soil). In the FABLE Calculator's analysis of the EAT–*Lancet* scenario, nitrogen use is reduced by 30% compared with the BAU scenario; however, water consumption and phosphorus use are only slightly reduced. Food system boundaries for nutrient and water use continue to be transgressed.

Combining the EAT–*Lancet* pathway with ecological intensification further reduces agricultural land area, water consumption, and nitrogen use, and substantially reduces greenhouse gas emissions to –0·51 Gt CO_2e (indicating carbon sequestration). Many of the ecological intensification practices used in the FABLE Calculator are not used in the ensemble models. Emission reductions are driven by increased sequestration on croplands (in soil) and, to a lesser extent, additional conversion of agricultural land to other uses due to enhanced productivity for some commodities. The FABLE Calculator results suggest that making substantial efforts to integrate ecological intensification practices in how food is produced within the EAT–*Lancet* scenario could contribute to achieving a net zero-emission food system. Estimates of the effect of the practices on soil organic carbon sequestration are taken from global meta-analyses and do not account for regional or local soil carbon saturation limits.[277] Results should therefore be interpreted with caution.

The most effective application of ecological intensification practices should be tailored to local contexts and co-selected with local farmers and landscape stakeholders to integrate local and scientific knowledge. The complexity of implementation at scale across multiple domains, and local carbon sequestration saturation points, could reduce both the speed of implementation, and the duration of carbon sequestration potential of ecological intensification.

	Land for agriculture, Bha	Cropland use, Mha	Land available for biodiversity,%	GHG emission, Gt CO_2e	Blue water use, M km³	Nitrogen use, Tg nitrogen	Phosphorus use, Tg phosphorus
Boundary (current state)	4·80 (4·56)*	None (16·08)	50% (50%)†	5·00 (6·76)‡	2·00 (4·63)‡	134 (234)‡	12 (29·4)‡
BAU	4·82†	18·53	48%†	7·35‡	5·37‡	306‡	35·9‡
EAT–*Lancet*	3·49*	16·00	56%*	2·75*	4·52‡	214‡	35·4‡
EAT–*Lancet* and ecological intensification practices	3·46*	15·69	56%*	–0·51*	4·41‡	211‡	34·4‡

Food, Agriculture, Biodiversity, Land-use and Energy (FABLE) Calculator (panel 6) comparisons with the food system planetary boundaries shown in table 2, and the current state (as of 2020). BAU=business as usual. *Results fall within boundary. †Results fall close to boundary. ‡Results fall beyond boundary.

Table 3: **Environmental impacts of food and land-use systems projected to 2050 under three future scenarios**

can increase yields, capture carbon, and reduce nutrient pollution.[312] Targeted feed improvements through continued reductions in wild fish use,[311] enhanced byproduct utilisation,[313] and improved conversion efficiencies of plant ingredients, can further help improve the environmental performance of aquatic foods.[314]

Section 3: justice in food systems

What is a just food system?

Justice involves the fair treatment of people, both as individuals and groups. Although various articulations of justice exist across disciplines and sectors (eg, philosophy, economics, sociology, and law), here we draw on three inter-related dimensions of justice that feature prominently in the literature on social and environmental justice: distributive, representational (or procedural), and recognitional (figure 8).[315,316] Distributive justice involves the fair distribution of important resources, opportunities, or capabilities (eg, healthy food, decent wages, and a clean, healthy, and sustainable environment) and the fair allocation of benefits and burdens.[38] Representational justice concerns decision making and power, including formal and fair policy-making processes, and broader societal decision-making processes.[315,317] This dimension of justice requires a fair distribution of power, the protection of key freedoms, and political voice and representation, including meaningful participation by those most affected by injustice. Recognitional justice manifests in the structures and norms of society, and recognises a diversity of intersecting identities and experiences that are shaped by cultural, legal, historical, and spatial contexts; recognitional justice involves people from all social groups being able to participate as equals.[315,317,318]

Our analysis concerns how these three dimensions of justice occur both within and across societies. For a society to be just, all people must experience distributive, representational, and recognitional justice, and, for global and international justice, these dimensions must also exist among nations and people worldwide.[317,319] In addition, our analysis encompasses both justice among people living at the same time (ie, intragenerational justice) and justice among people in different generations (intergenerational justice).[38] Intergenerational justice requires distributive justice across generations, including a fair distribution of benefits and burdens between current and future generations of people. Keeping food systems within planetary boundaries can help to ensure that environments are safe for people in the future, that healthy diets are accessible for all (especially young children and women of childbearing age), and that future generations remain healthy. Interspecies justice (another form of justice) concerns the fair treatment of other species by humans.[38] However, beyond recognising the need to remain within planetary boundaries—including keeping Earth within the 1·5°C climate threshold, and minimising biodiversity and environmental losses—we do not focus on interspecies justice in our analysis.

Establishing what counts as fair treatment for an analysis of justice requires consensus,[320] and, in the absence of a global process relevant to food systems, we chose to align our account of fair treatment with international human rights treaties and other instruments (figure 8).[321,322] These human rights instruments represent a consensus view of what constitutes the minimum acceptable standards for specific resources (eg, food) and opportunities (eg, work).[321] We use recognised human rights to identify justice-based entitlements, and to specify and quantify minimum acceptable levels of resources and opportunities to support justice within food systems (figure 9; table 4; appendix 4 pp 2–8). Because all human rights are universal, indivisible, interdependent, and inter-related, we focus on three rights closely related to food systems: the right to food, the right to a healthy environment, and the right to decent work. We also draw on international human rights' commitments to non-discrimination, participation, and civil and political rights. The concept of agency is essential for our account of justice within food systems. Agency, understood as people's capacity to make choices that shape their own circumstances and to use their voice by participating in broader societal decision-making processes, is an important contributor to food security, secure livelihoods, and to addressing inequities within food systems[324] (appendix 4 pp 6–7).

See Online for appendix 4

Justice requires that everyone—regardless of their social identity—has their rights to food, a healthy environment, and decent work realised, and has a political voice and fair representation. Achieving justice is therefore dependent on the social systems (and other conditions) that can promote or hinder it. These systems

Panel 7: Challenges and changes in livestock production

A food systems transformation aligned with the EAT–*Lancet* scenario would mark a paradigm shift in our relationship with farmed animals (Gibson MF, unpublished manuscript), with a considerably transformed and smaller livestock system globally (figure 7). To match nutritionally healthy meat consumption in the human diet, we estimate that livestock numbers would decline globally to 1·1 billion ruminant animals (eg, cattle, sheep, and goats) per year (a 26% reduction); dairy animals to 785 million per year (a 4% reduction); and non-ruminants (of which >95% are poultry and <5% are pigs) to 66 billion per year (a 19% reduction). Conversely, fish production would increase to 220 million tonnes per year (a 46% increase from 2020 levels). With regard to the value of production, we see an absolute contraction from 2020 levels, with a 43% decline across the global terrestrial livestock sector (a reduction of $650 billion) by 2050. Proportionally, this reduction is more marked for ruminant meat (71%) than for non-ruminants (46% reduction) or dairy (20% reduction). The decline also represents a 50% reduction in terrestrial livestock sector employment by 2050; however, in a business-as-usual scenario, we see a reduction of around 25%.

Changes in livestock numbers indicate reductions in methane and nitrous oxide emissions (22% reduction versus 2020 emissions) and grazing lands (11% reduction versus 2020; ~340 Mha). Further improvements in practices should be developed and applied to further reduce emissions and to increase and capture the environmental benefits of livestock production. For example, some of the methane emissions linked to ruminant management can potentially be mitigated in the future (figure 4).[263]

The meat and dairy sectors are the most affected by shifts to healthy diets. Although we recognise the contentious and complex nature of animal-sourced food production and consumption, a smaller livestock sector creates opportunities to improve animal health and wellbeing, environmental outcomes, and labour quality. We flag six important opportunities and considerations to navigate this transition, which we recommend considering in combination rather than in isolation.

Gains through efficiency and technology

Substantial efficiency gains in production exist, especially in low-income countries, that can markedly reduce the anticipated environmental and health impacts of production. Emissions intensity can be improved so that fewer greenhouse gas emissions are emitted per unit of production.[279] Caution is urged around other environmental effects of densely occupied, confined systems, such as concentrated nutrient pollution, disease risk, overuse of antimicrobials, animal health and welfare, and labour conditions. The assumed conservation gains of improved efficiency are only attained with complementary policies and actions that restrict, for example, continued expansion into intact lands.

Zero conversion of intact forests and grasslands

The additional conversion of forests for pasture or feed systems is antagonistic to achieving both human and environmental goals. The destruction of intact grasslands is often overlooked, but these spaces are even more threatened than forests globally. Only 30% of intact grasslands are remaining, making them the most converted but least protected ecosystems globally.[280]

Gains through nature-positive rangeland management

Although intensive grazing contributes to land degradation,[281,282] integrating grazing livestock to grassland maintenance is also a possibility for conserving and restoring grassland ecosystems.[283] Soil organic carbon is estimated to increase from 2·3 to 7·3 Gt CO_2 equivalent (CO_2e) per year for grassland restoration in general; improved grazing management could provide a further 0·15 to 0·7 Gt CO_2e per year.[284] Grazing management can be improved in different ways, from complete removal of grazing livestock to reduced grazing intensity, but these improvements should be balanced with agroecosystem conditions.[283] The production of supplementary feeds should be included in the overall effects of livestock production systems (eg, deforestation).[285] In forest biomes, silvopastoral systems present an opportunity to mitigate the effects of livestock production and contribute to productivity gains.[286]

Gains through integration

Modern agriculture has often separated animal and plant productions systems. Methods reconnecting these systems, whether integrated in landscapes or connected through circular production systems (eg, insect-based feed), offer promise.[287–288] Feeding livestock with byproducts in circular systems has potential, but the number of animals that could be reared is limited by the availability of such feed, resulting in substantially lower production levels than what is currently produced.[289]

Gains in animal welfare

Perspectives emphasising the welfare and wellbeing of animals in agriculture have risen due to a growing concern related to intensive, confined, and industrialised farming systems (ie, factory farming). High stocking densities,[290,291] long transportation times,[292] and practices that restrict natural behaviour[293] all pose animal welfare concerns, and extensive systems also come with their own challenges.[294] Animal welfare concerns and the quality of the produce are factors shown to influence consumer choice, even outranking environmental concerns.[295] Discussions on animal welfare and wellbeing should reflect multidisciplinary knowledge and research on animal cognition and behaviour, veterinary science, and ethics.[296]

(Continues on next page)

(Panel 7 continued from previous page)

Foods sourced from non-ruminant animals

In some regions of the world, beef consumption has plateaued or is declining (eg, in the USA and Europe), with poultry and pork driving increases in per capita animal-sourced food (or meat) consumption. Aquatic foods are common to many cultures and traditions and are a healthy source of animal protein. Animal-sourced foods will generally have higher environmental footprints than plant-sourced foods because of the lost energy conversion between trophic levels. This loss is lowest for aquatic and avian-sourced foods and can be further mitigated by more circular systems. However, most livestock production systems share similar disease and pollution risks at scale, especially in dense, highly confined systems, and all have concerns related to animal health and welfare.

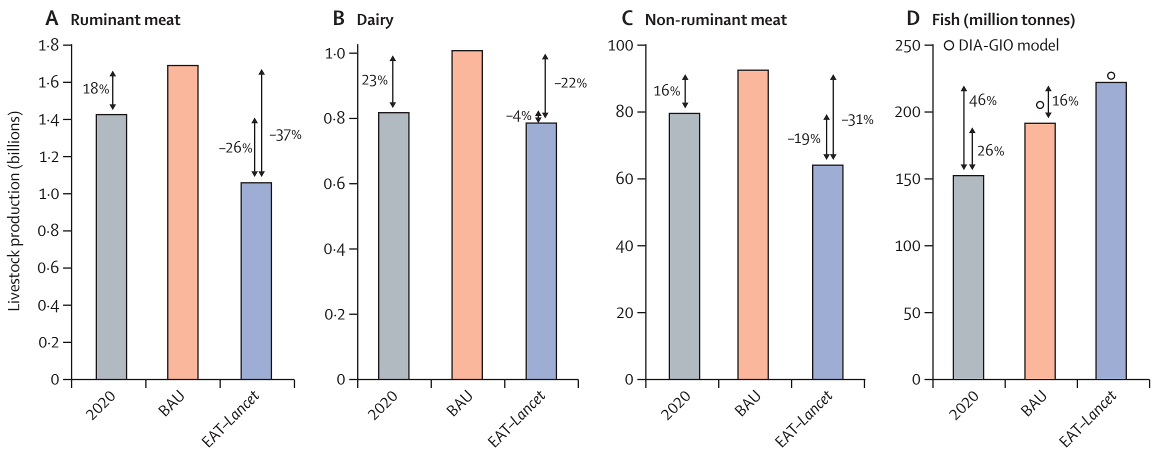


Figure 7: **Projected changes in livestock and fish production under BAU and EAT–*Lancet* scenarios**

(A) Global animal numbers for ruminant meat (ie, cattle, sheep, and goats). (B) Global animal numbers for dairy. (C) Global animal numbers for non-ruminant meat (ie, poultry and pigs). (D) Global fish production (in million tonnes). The grey bar gives current animal numbers based on data from the Food and Agriculture Organization of the UN.[297] The red bars give projected numbers from modelling in a BAU scenario; the blue bars give projections for an EAT–*Lancet* scenario. The unfilled black marker in (D) gives results for the DIA-GIO model. Note that different units of measurement are applied for each category. BAU=business as usual. DIA-GIO=Global Input–Output module of the Dietary Impact Assessment model.

include political institutions, economic systems, cultural institutions, and their interaction. These interactions result in different kinds of voices, power, and agency for governments, businesses, food producers and workers, civil society organisations, and social systems (eg, within food, health, or education). People are unevenly affected by these social systems, with some groups systematically having fewer resources and opportunities than others, as well as less voice, power, and agency, leading to structural inequalities that perpetuate their vulnerability (panel 8). Achieving justice might therefore require a fundamental transformation of these political systems, but this goes beyond the scope of this Commission. Instead, we focus on the need for justice for people within food systems, and how to address their specific needs.[318]

Social foundations

We operationalise our justice analysis through the lens of social foundations, which require basic human rights (eg, food, water, health, and energy) to be met for everyone.[333,334] Previous work has focused on defining the minimum resources required to meet people's human rights, to avoid resource deprivations and

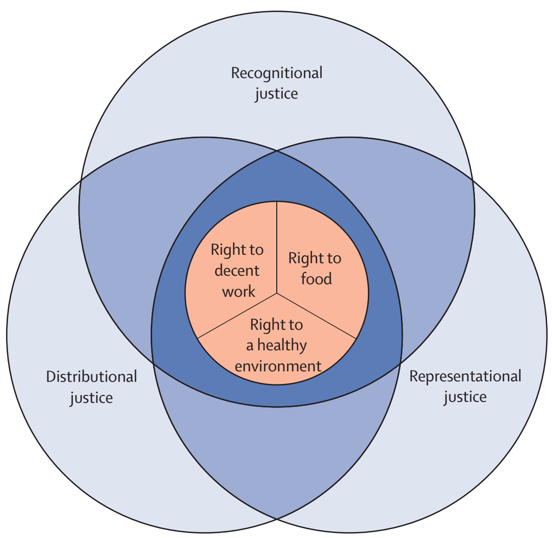


Figure 8: **Conceptual framework of the justice section**

The three justice dimensions and three human rights are inter-related and inter-dependent. Achieving the three justice dimensions of distributive, recognitional, and representational justice requires meeting the three human rights.

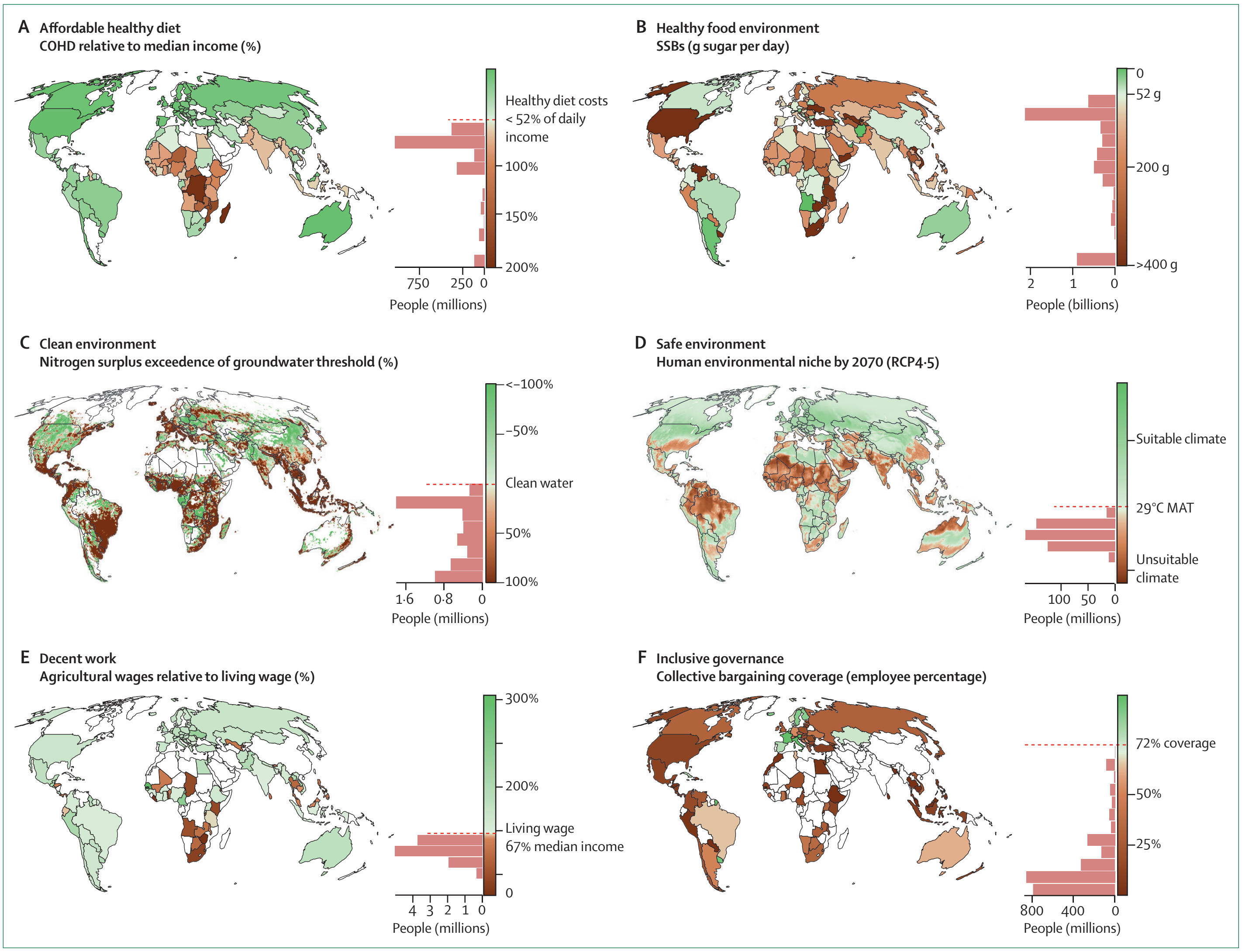


***Figure 9:* The global status of social foundations in food systems**

Each panel visualises one of six (out of eight) proxy variables and its corresponding social foundation (table 4). Maps show the global distribution of values, with places that fall below the social foundation in brown, and those where the social foundation is intact in green (white indicates no data available). Histograms on the colour legends indicate the total number of people that fall below each social foundation. Variables are: (A) COHD (social foundation: a healthy diet costing <52% of national average income); (B) consumption of SSBs (social foundation: consumption of added or free sugars <10% of total energy intake); (C) nitrogen leaching into groundwater (foundation: exceedance of WHO's safe limit for drinking water [0%]); (D) changes in the suitability of the human environmental niche between current conditions and RCP4·5 in 2070 (foundation: heat exposure; MAT ≤29°C); (E) agricultural wages relative to a living wage (foundation: wages >67% or 55% of median incomes in each country); (F) access to collective bargaining (foundation: collective bargaining coverage >75% of employees). Data sources and variable definitions are available (table 4; appendix 4 pp 10–12). Data were unavailable for countries in white, except for nitrogen exceedance (C), where white values indicate non-agricultural lands. COHD=cost of a healthy diet. MAT=mean annual temperature. RCP=representative concentration pathway. SSBs=sugar-sweetened beverages.

harms.[38,334] However, the availability of resources alone is insufficient to avoid these harms.[335] Therefore, we instead focus on the conditions that enable human rights to be met. We specify conditions (ie, social foundations) that would help enable each of the three rights (ie, food, decent work, and a healthy environment) to be realised (table 4). Through a combination of expert consultation and a literature review, we first identify the individual and cross-cutting food system components relevant to each human right. Next, and drawing on the outcomes from a multi-stage, multi-stakeholder evaluation of food systems indicators,[34] we identify a suite of candidate indicators for each component and assess their coverage, scale, relevance, and overlap. Where indicators for key food system components were not available (eg, individual and collective agency) we reviewed the literature to propose additional indicators for development and monitoring.[323] Our final selection includes a set of indicators that convey discrete dimensions of the conditions that enable people's rights to be met, rather than the outcomes of these rights being met (or not

	Proxy variables	People below foundation	Social harms	Extent of harm	Harms figures
Right to food					
Affordable healthy diets (COHD <52% average income)	COHD	2·8 billion people globally cannot afford a healthy diet	Moderate or severe food insecurity; low birthweight; unsafe drinking water; anaemia in children	2·3 billion people (29%)* experience food insecurity; 19·8 million newborn infants (15%)* are of low birthweight; 2·1 billion people (27%)* exposed to unsafe drinking water; 269 million children† (40%) are anaemic	Figure A3·1 (appendix 4 p 13)
Healthy food environment (national intake of sugar from SSBs at <10% of total energy intake)	Intake of SSBs	5·6 billion people globally live in countries with a national average intake of sugar >10% of total energy intake	Diets high in SSBs; unhealthy diets; obesity	75 725 deaths per year are linked to diets high in SSBs; unhealthy diets account for the loss of 3·6 million DALYs; >1 billion people have obesity (16%)*	Figure A3·1 (appendix 4 p 13)
Right to a healthy environment					
Non-toxic environments (nitrogen leaching <50 mg nitrate/L)	Nitrogen leaching from agriculture	5 billion people exposed to unclean water above WHO limit	DALYs from unsafe water sources	Unsafe water sources account for the loss of 42 million DALYs	Figure A3·2 (appendix 4 p 14)
Safe climate (MAT ≤29°C)	MAT change	419 million people will be exposed to MAT ≥29°C by 2070	DALYs from high temperatures	High temperatures account for the loss of 14 million DALYs	Figure A3·2 (appendix 4 p 14)
Right to decent work					
Food system worker wages greater than a living wage‡	Food system worker wages	394 million (32%) food system workers earn below a living wage	Child labour	159 million children§	Figure A3·3 (appendix 4 p 14)
Meaningful representation (coverage in collective bargaining >72%)	Collective bargaining coverage	2·6 billion people cannot participate in collective bargaining processes	Gender wage gap	50% gender wage gap in agri-food systems	Figure A3·3 (appendix 4 p 14)
Individual and collective agency (encompasses all rights)					
Freedom from corporate control (CR4 <40%)	Market share held by the top four firms in the sector (CR4)	Not determined	Higher food prices, suppressed wages, weakened livelihood opportunities, undermining working conditions, lobbying, weakened representation	Clapp et al (2025)[323]	..
Civil and political freedoms	Freedom of expression index	Not determined	..	..	Figure A3·4 (appendix 4 p 15)
Non-discrimination	Social institutions and gender index	Not determined	..	..	Figure A3·4 (appendix 4 p 15)

For each variable we specify the level at which the social foundation could be met. Falling below these social foundations results in a range of specified harms. We estimate the number of people currently falling below these social foundations and the extent of social harms globally. COHD=cost of a healthy diet. CR4=four-firm concentration ratio. DALY=disability-adjusted life-years. MAT=mean annual temperature. SSBs=sugar-sweetened beverages. *Percentage of global population. †Children aged 6–59 months. ‡Living wage is defined as being greater than a 67% median wage in low-income countries and 55% in high-income countries.[19] §Child labour includes children aged between 5–17 years who are in work that is hazardous to their health, safety, or morals.

Table 4: **Social foundations grouped by their applicable human rights, and the proxy variables that allow conditions to be tracked**

met), which act as our proxy variables (appendix 4 pp 2–8). For each proxy variable, we specify the threshold at which the social foundation would be considered met, estimate the number of people falling below each social foundation globally, and examine the extent of harms associated with each of the three human rights not being realised (table 4; appendix 4 pp 13–15).

Evaluating injustices

The right to food

The right to food involves the right to a secure and stable supply of sufficient quantities of affordable, healthy, culturally appropriate, and sustainably produced food that considers peoples' practices and customs, to ensure all forms of malnutrition can be avoided, and a dignified life supported.[336,337] Beyond the right to access sufficient food for a healthy diet, the right to food also places responsibilities on states to promote good nutrition and health, through measures such as food advertising regulations, labelling requirements, and other actions that shape food environments to encourage healthier diets.[336,338] We therefore identify two social foundations linked to the right to food: healthy affordable diets and food environments that do not undermine people's capacities to make healthy choices (which we refer to as healthy food environments).

The Food and Agriculture Organization of the UN considers healthy diets to be affordable when they cost less than 52% of average household income.[339] We therefore align our minimum condition and social foundation for affordable healthy diets with this definition (table 4). In 2022, 2·8 billion people globally were below the minimum

Panel 8: Recognitional injustices—the need for attention to gender and intersectionality

Distinct groups of people—women, men, and children—of different income levels, social statuses, ethnicities, and geographical locations have different livelihood opportunities and nutritional needs. They also have differing levels of choice in terms of how far they can access and afford healthy diets and decent work. Not paying attention to these group differences can lead to significant harm, not only for the individuals concerned, but for humanity more broadly by losing contextual knowledge and practices (eg, Indigenous farming practices).

Minority ethnic populations and Indigenous people are often at the greatest risk of losing their livelihoods and access to healthy and culturally important food. These risks usually start with a loss of access to land or natural resources (eg, forests) through unjust conservation or extraction policies (eg, exclusion from management),[325] or insufficient protection policies. Many of these marginalised groups—particularly women from minority groups—also face discrimination and major structural barriers that are rooted in colonialism, racism, and patriarchy, leading to reduced access to technology and training opportunities, and under-representation in political and managerial positions.[326,327] These barriers are detrimental to building decent and resilient livelihoods.

People living in countries with conflict are especially marginalised. Hunger and starvation have often been used as political weapons of war, and continue to be used as such today, through intentional destruction of food systems (especially of agricultural lands [eg, Sudan, Ukraine, and Palestine]), withholding or restricting food aid (eg, Yemen and Palestine), and unilateral coercive measures (eg, Sudan, Venezuela, and Syria). The impact of these conflicts has spread across the global food system and affected the availability and price of food and other resources (eg, fertiliser), especially in rural locations and for people with low income.[328] Conflict and war therefore lead to further marginalisation and directly or indirectly cause hunger, food insecurity, and famines, undermining the right to food for all[329] and particularly affecting people with low income, minority groups, women, and children.

These characteristics of injustice are not exhaustive, as marginalisation can manifest differently across and within regions or countries. Furthermore, the opportunities people have access to often differ based on the intersection of key characteristics, such as wealth or poverty, with gender, geographical location, age, and ethnicity. For example, in middle-income countries, women tend to be more food insecure than men (appendix 4 p 13). However, women appear to have greater dietary quality than men, especially in high-income countries (appendix 4 p 13). Meanwhile, poverty is increasingly urbanising at a global scale, leading to insufficient access to healthy foods for people with low income who live in urban areas—a problem that emerges, in part, due to a changing climate and the migration of these people from rural to urban areas.[330]

An intersectional lens (ie, paying attention to multiple injustices and aspects of identity that intersect to exacerbate the experience of marginalisation) is therefore key to identifying the specific vulnerabilities affecting marginalised people.[331] This lens requires sufficient levels of data disaggregation across contexts, and the recognition of alternative knowledge systems, especially those from Indigenous communities.[332] However, data remain skewed towards particular social groups and geographical regions: evidence from Canada and the USA suggests that migrant workers face poor and dangerous working conditions and food insecurity, but literature on migrant workers in other regions, especially low-income and middle-income countries, is scarce.[34] Similarly, some regions, such as the Middle East, are persistently under-represented in the published literature.

condition for an affordable healthy diet. The inability to access sufficient quantities of healthy food causes diet-related harms that extend beyond their immediate impacts to damage economies and increase risk of conflict and disease. In the same year, 2·3 billion people were food insecure and 1·8 billion had no access to clean water—conditions that are strongly linked to poor food safety and nutrient absorption (table 4; figure 9; appendix 4 p 13).

The extent to which regions fall below these minimum conditions, and the severity of their associated harms, differ across geography and social group (ie, ethnicity, gender, and wealth). Although the rapid globalisation of the food system through trade and subsidies has made more food available globally and has lowered food prices, it has also suppressed wages and the prices producers receive, leaving healthy diets least affordable in LICs and lower-middle-income countries (LMICs), where food insecurity, low birthweights, and anaemia are also most prevalent (figure 9, appendix 4 p 13). These countries are also where most food systems workers live, often leaving them the least able to afford a healthy diet.

Although justice requires that healthy food becomes more affordable and available, this will not necessarily result in healthier diets.[7,340] As economies develop and family incomes grow, healthy diets become more affordable but ultra-processed foods, red meat, and sugar-sweetened beverages also become more available and exposure to unhealthy food advertising increases.[340–342] As a result, diet quality globally is lowest in upper-middle-income countries (UMICs) and high-income countries (HICs), particularly among men, and rates of overweight and obesity are highest in these same regions, particularly among women (appendix 4 p 13). Furthermore, although healthy diets are more affordable in HICs, they remain unaffordable or inaccessible for many, resulting in lower diet quality and higher obesity rates for people with low incomes compared with those with high incomes.[343,344] By contrast, in UMICs such as those in Latin America, high-income groups have a poorer diet quality than low-income groups despite being more food secure. This poor diet is probably due to the hyper-availability of unhealthy foods.[345] Rapidly changing food environments and unequal access to housing, water, health, and market services mean LMICs and UMICs, particularly in urban and peri-urban areas, are now epicentres of multiple forms of malnutrition and its associated outcomes (appendix 4 p 13).[7,346] These regions are also where most of the global population currently lives, and where most future population growth will occur, underscoring the critical global importance of healthy diets being available and affordable within a food environment that is conducive to healthy choices.[30]

Food environments are the physical, economic, political, sociocultural, and digital contexts in which consumers engage with the food system to make decisions about acquiring, preparing, and consuming food.[347] Food environments and food choices are increasingly shaped by advertising and commercial marketing; as a result, expenditure on marketing of unhealthy food would be an apt proxy variable for healthy food environments. However, global data on this variable are absent. As an alternative proxy indicator for an unhealthy food environment, we use sugar intake from sugar-sweetened beverages, which is associated with cardiometabolic disease and social inequities.[348] We align our minimum condition for a healthy food environment with WHO's recommendation of less than 10% of a person's total energy intake being from free or added sugars (ideally reduced to <5%, as used in the PHD).[152] In 2018, 5·6 billion people globally were below the minimum condition of a healthy food environment, with their intake of free or added sugar exceeding 10%. Excessive sugar intake from sugar-sweetened beverages are associated with overweight or obesity in 2·5 billion adults and 360 million children and adolescents, and more than 75 000 early deaths (table 4; appendix 4 p 13).

Food environments determine food choices in complex ways, whereby the contexts in which consumers engage with food interacts with the affordability, availability, accessibility or convenience, and desirability of foods (especially for healthy food *vs* unhealthy food).[349] Although higher incomes can promote greater diet diversity, the type of food environment an individual is exposed to can weaken or strengthen this relationship.[349] In the face of rising corporate concentration and increased marketing of unhealthy food, territorial and local markets—with a focus on small-scale and informal actors—have the potential to revitalise and stabilise local production, and enhance healthy food choices for poor people.[346] This potential becomes especially important in UMICs and LMICs, in which rapid urbanisation is changing food environments and creating food voids (ie, environments lacking in food), food deserts (ie, areas where sufficient healthy food is inaccessible),[347] and food swamps (ie, areas where unhealthy and ultra-processed foods[350] are abundantly available, accessible, and affordable).[347] These changes have previously been seen only in HICs.[346] In each of these cases, people are at increased risk of food insecurity, micronutrient deficiencies, overweight or obesity, and non-communicable diseases.[346,347,351,352] Low diet quality could be due to inadequate availability, accessibility, or affordability of healthy foods, or because unhealthy foods are abundantly available, affordable, and convenient.[347]

Changes in food environments have also accompanied changes in food cultures. The shift to unhealthy diets is characterised by a loss of traditional foods and food deskilling (ie, a loss of cooking skills and knowledge).[340,353] Changes in food cultures can be explained by several factors. First, time poverty has increased, especially for families in which both mothers (who largely remain in charge of food provisioning, despite improvements in gender equality) and fathers (who, in some cultures, are largely uninvolved in food preparation) work.[354,355] Second, the loss of local biodiversity (particularly of cultivated and foraged species) and insufficient access to resources have affected healthy food provision in some regions, especially among Indigenous communities.[356] Children are especially susceptible to unhealthy food advertising, which can lead to the development of unhealthy food habits that persist into adulthood. Shifts to unhealthy diets can involve moving food culture away from traditional foods and family meals. These changes have implications for diets and health, but equally for the acquisition of food knowledge and skills, especially for children.[357]

The right to a healthy environment

The right to a healthy environment rests on the recognition that the right to food (and many other rights) requires a clean, healthy, and sustainable environment. This right encompasses several substantive rights, including to a safe climate and a non-toxic environment, which we adopt as two social foundations of this right.[358] Climate conditions habitable for humans have been broadly characterised as land with a mean annual temperature of 29°C or less,[359,360] and we use this as our minimum condition for a safe climate. By 2070, 419 million people globally are projected to exceed the minimum condition for a safe climate. In 2022, high temperatures[38] accounted for the loss of 14 million disability-adjusted life-years (DALYs; figure 9; table 4; appendix 4 p 14).[9] Climate impacts are and will continue to be experienced inequitably, intersecting with poverty and geography to disproportionately affect specific people and regions. Climate change will exacerbate experiences of food insecurity for many LICs across Africa and for people living in poverty, despite them being the least responsible for their plight.[361,362] Meanwhile, women—particularly those living in rural areas, LMICs, and Indigenous communities—and agricultural producers and workers are more likely than men and non-agricultural workers to have their livelihoods undermined by climate change, and to experience physical injury and ill health as a result of harmful work conditions.[363–365] Within food systems more generally, women, children, Indigenous and rural communities, and people living in poverty are most affected by unsafe and unhealthy environments because of their marginalisation.[366]

A wide range of food system pollutants exist that create toxic environments and have negative human health effects (panel 2).[38] Due to data availability, we focus only on nitrogen leaching to groundwater, of which 75% comes from agriculture.[38] Nitrogen pollution is connected to adverse reproductive effects and cancer in humans.[38,51] WHO guidelines specify a safe level of nitrogen for drinking water as 50 mg NO_3^- per litre,[367] which defines our minimum condition for healthy environments. In 2022, 5 billion people globally fell below this minimum condition and were exposed to unsafe levels of nitrogen leaching, which was associated with the loss of 42 billion DALYs (figure 9; table 4; appendix 4 p 14) and 4 million new cases of paediatric cancer per year.[9,38,51,367] As with the right to food, these harms are not distributed equally. People living in rural locations are most likely to be affected by agricultural pollution,[368,369] and the poorest regions of the world (particularly across Africa, south Asia, and China) experience the greatest number of DALYs due to unsafe water, with as little as 10% of rural populations having access to clean water (appendix 4 p 14).

The right to decent work

The right to decent work[21,370] entails the right of everyone to live in dignity;[19,370,371] to work in just and favourable conditions; to be free to choose their work, with a salary that allows them to live and support a family; and to receive equal pay. We identify two social foundations linked to the right to decent work, namely a living wage and meaningful representation. A living wage conveys the minimum renumeration necessary to support an acceptable standard of living for a worker and their family.[370,371] Although not always implemented, a legal minimum wage has been set in 90% of the 187 countries within the International Labour Organization (ILO) agency. This minimum wage equates to an average of 67% of the median wage in LICs and 55% in HICs,[19] which we use as the social foundation of a living wage. In 2022, an estimated 34% of the food system workforce—including agricultural, non-agricultural, formal, and informal workers—was below the social foundation of a living wage, women earned 50% of what men did, and 159 million children were involved in child labour, predominantly in agriculture (table 4; figure 9; appendix 4 p 14).[372,373] Policies are needed that balance the competing need of ensuring healthy food is affordable while also providing adequate and liveable renumerations.

Women's work in agriculture remains undervalued and is often seen as an extension of domestic chores.[374] Women are often paid by the piece (rather than by the hour, as men are), and their wages are sometimes given to male relatives, hindering their economic independence.[375] If gendered wage gaps in agricultural labour remain unaddressed, food system injustices are likely to worsen because of the ongoing feminisation of agriculture in all regions other than in HICs.[376] This feminsation is due to men leaving for non-farm work to obtain more stable and lucrative livelihoods (eg, in construction), inflating the presence of women in a low-paid sector.[377] Furthermore, sexual harassment due to power imbalances between female farm workers and employers remains pervasive (eg, studies have reported incidences of 24–93% in the USA), with few opportunities for reporting due to stigma and risk of retaliation.[375] However, food system injustices are not limited to women: in the USA, male migrant farm workers also face abuse and exploitation.[375] Justice and the right to decent work require living wages for all food systems workers, regardless of their gender and any other forms of marginalisation.

Collective bargaining is one way to enable the meaningful representation of both workers and employers and ensure that opportunities to regulate the conditions of work are present.[378] The right to collective bargaining is a fundamental ILO convention[379] and an enabling right that facilitates inclusive and effective governance of work, ensuring decent wages and working conditions, and social protection.[378] Collective bargaining can facilitate equality, contribute to safe and healthy workplaces, and build resilience within a workforce, but its coverage varies considerably worldwide. We set our social foundation for meaningful participation at a collective bargaining coverage rate of 72% of employees, which, although below the EU's threshold of 80%,[380] is equivalent to the rate found by the ILO in multi-employer settings to be more successful. Between 2008 and 2020, 2·6 billion people globally were below the social foundation of meaningful representation, with no access to collective bargaining (figure 9; table 4).[381]

Collective bargaining rates are highest in HICs, reaching nearly 100% in some countries (eg, Italy and France), but are low in LMICs, ranging from 0% to 40% and being close to just 1% in some countries (eg, Malaysia and Paraguay).[378] The majority (69%) of the approximately 1·02 billion people employed in food systems that support an estimated 3·8 billion people[373] are found in LMICs within Asia or Africa (appendix 4 p 14).[382] Most of these jobs are informal, seasonal, unregulated, and unmonitored; workers are often living in poverty, reflecting their low levels of representation. Average agricultural wages are near or below national minimum wages (appendix 4 p 14),[19] making food systems workers one of the groups that are least able to afford a healthy diet. However, in these LMICs, nearly 50% of all employment is within the agricultural sector (appendix 4 p 14),[383] underscoring the considerable and cascading importance of meaningful representation for these workers.

Despite generally high levels of collective bargaining in HICs, recent shifts in food systems towards more concentrated systems and specialised units of production (eg, intensive production of a single crop or species with high technological inputs, such as salmon or chicken) have undermined worker participation, resulting in poor labour standards and animal welfare.[384] This undermining is partly due to informal arrangements or zero-hour contracts being the norm among small and medium enterprises in LMICs and some HICs.[385,386] Evidence suggests that although informal enterprises can be highly organised and streamlined, labour conditions can be exploitative, including for children.[387,388] Forced labour is prevalent on land and at sea, in both LMICs and some HICs, including the US food supply chain.[389] Therefore, a just food system would include food systems workers (especially smallholders) earning a living wage, with access to collective bargaining and the ability to advocate for their rights and working conditions.

Individual and collective agency

Agency—people's capacity to make choices that shape their own circumstances and to participate in broader societal decision-making processes—has been recognised as an important contributor to food security, nutrition, secure livelihoods, decent work, healthy environments, and to addressing wider inequities within food systems. However, ample evidence exists on how people's freedoms and agency are curtailed within current food systems.[390,391] We therefore recognise individual and collective agency as not just important in themselves, but specific forms of agency are also, arguably, emebedded and implicit in the concepts of human rights. Human rights emphasise the importance of rightsholders participating in decisions that affect them, and human rights treaties and other instruments include many rights guaranteeing civil and political freedoms, and specific forms of choice or control for individuals and groups. Human rights are committed to eliminating discrimination. Taken together, these components of human rights embody a broad commitment to individual and collective agency. Because fully quantifying the concept of agency is impossible, and identifying variables that capture agency in a capacious sense is challenging, we propose three social foundations and related proxy variables that capture three facets of agency: non-discrimination, freedom from corporate control, and civil and political freedoms.[323,324,392,393]

People's agency—their capacity to make choices and participate in decision making—can be constrained by structural inequalities shaped by social position and identity, particularly class and gender. Ensuring that all people have agency therefore requires addressing discrimination in all its forms, including inequalities in access to key resources and services, unjust power differences between groups, and intentional discrimination. As a proxy variable for non-discrimination, we use the Social Institutions and Gender Index,[394] which measures discrimination against women; however, this indicator does not fully capture discimination given the presence of discrimination against many distinct groups.

Discrimination against women is prevalent globally, but is highest in south Asia, the Middle East, and north Africa, as well as many parts of sub-Saharan Africa (appendix 4 p 15). In no country in the world are women afforded the same opportunities as men that allow them equal representation in government or in the workforce more broadly, undermining their access to decent work and healthy food.[395] Agency is therefore about inequality and choice, with particular emphases on the "inequalities in people's capacity to make choices rather than in differences in the choices they make".[392]

Highly concentrated market structures, in which just a few firms dominate key steps along food supply chains,[396] can signal power imbalances where dominant firms can exercise market power that enables them to generate excess profits due to weakened competition.[20,397,398] The exercise of market power by large firms can in turn undermine agency within food systems, especially for the most marginalised populations. Most economists agree that the likelihood of firms exercising market power increases when the top four firms control over 40% of the market.[398] Although other metrics are also often used, due to data limitations we focus on the top four-firm concentration ratio, for which data are more available, and specify 40% as our minimum social foundation for freedom from corporate control. A four-firm concentration ratio above 40% would indicate people's agency is at risk of being curtailed and therefore requires further investigation (table 4).

Evidence has shown a very high degree of corporate concentration along food supply chains, with just a few large firms dominating international markets for agricultural inputs (eg, seeds and fertilisers), agricultural commodity trade (eg, soybeans and poultry), some processed and packaged foods (eg, biscuits, confectionary, and soft drinks), and national markets for food retail.[14] Access to market power is extensive in food systems, allowing dominant firms to set prices and generate excess profits.[20,23] Concentrated firms' capacity to raise prices for seeds, fertiliser, grain, or packaged foods impacts people's access to food and influences which food they can and cannot consume. Dominant firms that source from smaller scale food producers have a degree of buyer power, meaning they can dictate the prices they are willing to pay producers and other suppliers (eg, workers), therefore directly impacting suppliers' incomes and ability to access food.[23]

Large firms and concentrated commercial activity also shape the material conditions within which choices are made through their business decisions. For example, corporate strategies to reduce costs that affect food production practices could increase the level of processing or unhealthy content of packaged convenience foods, which—when coupled with manipulative advertising and packaging—can have widespread impacts on food consumption environments, resulting in poor product choices and increased consumption of less healthy foods.[23,399] Business decisions of dominant firms have a disproportionate effect on agricultural production technologies; labour conditions for food system workers, including (in some cases) forced labour;[400] and environmental practices,[401] which directly affect producers' and consumers' options. Large and dominant firms in concentrated markets can influence policy and governance processes in ways that affect democratic participation in food systems governance, which can directly undermine agency.[20] This influence is through direct lobbying as well as indirect means, including sponsorship of research by firms, lobby organisations, and interest groups, and close relationships and a lack of independence between industry and government, influencing measures such as dietary guidelines and regulations within food systems,[402,403] and often drowning out citizens' voices in policy-making processes.

Measuring the effect of corporate power on human agency in food systems is not straightforward, in large part because well established metrics for agency do not exist,[324] and firms' data on their market share, marginal profits, and mark-ups (ie, the amount they charge over and above their costs) are not always publicly available. Corporate concentration (as measured by the four-firm concentration ratio) and profit data can usefully serve as proxy indicators to identify where corporate power might exist within food systems. However, food systems market data, at both global and national scales, is often unavailable or behind prohibitive paywalls, presenting challenges for assessment of these dynamics. We therefore underscore the need for companies to make profit and mark-up data available, enabling the tracking of an indicator of market power.

Although this approach would benefit from more transparent data reporting from firms, these indicators highlight markets where dominant firms are more likely to influence food systems in ways that can constrain people's agency. Stronger policies are needed at national and international levels to prevent corporate concentration from subverting agency, both in the market and through other forms of power available to large and dominant firms. More robust competition policies, for example, can help in preventing excessive market power and ensure prices remain fair for both buyers and sellers.[23,404]

We focus on freedom of expression as an important facet of individual and collective agency, because it allows citizens and governments to be better informed, enables civil society to hold corporations to account, and helps to sustain a range of other human rights.[22] However, and particularly in parts of the Middle East, north Africa, eastern Europe, and Asia, freedom of expression is markedly curtailed, which undermines agency (appendix 4 p 15). Although indicators can never fully capture complex concepts, as policies and laws are mediated by social context, the V-Dem freedom of expression index[405] captures the extent to which a government respects freedom of press and media, freedom of people to discuss political matters at home or in public, and the freedom of academic and cultural expression. Although countries with laws that uphold freedom of expression might actually curtail freedom in practice (and vice versa), we draw on this index as a preliminary indicator in the absence of more nuanced data.

When people have agency to participate in food systems governance and decision making in meaningful ways, they can shape their food systems to make them more just. Multiple possibilities for civil society and citizen engagement exist in democracies, including on matters related to food systems, such as elections, public debates, and consultations on keys laws and policies.[7] However, where these opportunities to engage are inadequate due to discrimination, exclusion, or an absence of freedom of expression (table 4), people are more likely to be marginalised and exposed to harm, and might take action through protests or other forms of movements.[21]

With the growing concentration of power—financial, technological, economic, and political—within few firms across many food systems, citizen agency is increasingly claimed or manifested through diverse forms of food activism. These forms of food activism span rights-based movements for justice, reactive street protests, alternative food systems governance structures (ie, citizen-led movements), initiatives safeguarding the quality and cultural significance of food, and other modes of individual and collective advocacy.[406] Movements for food justice and protests often involve marginalised groups—farmers, women, Indigenous populations, and rural communities—and are motivated by concerns about food and nutrition security, prices and affordability, and livelihoods, and seek the implementation of the basic right to food. However, despite challenging the growing concentration of power within the food system, farmers' protests (such as those seen recently in Europe) might contradict more ambitious state policies to address climate change or food system transformations.[407] Nonetheless, citizens' freedom of expression and other aspects of agency remain central to addressing structural inequalities and discrimination within the food system.[406,408]

The nature of state responses to citizen agency varies, ranging from neglect or repression to concessions and even policy change. Widespread citizen consultation opportunities during decision-making processes should not be taken for granted.[406] States can appear responsive to movements for food justice, often to avoid political conflict or public critique, but can also be driven by the global push for sustainability.[407] Different forms of citizen agency and their associated state responses give voice to diverse groups of stakeholders affected by food system changes and are key to representational justice.[406]

In summary, agency is a social foundation for the rights to food, decent work, and a healthy environment, and is crucial for implementing justice. Freedom of expression and other civil and political freedoms support agency within food systems, whereas corporate concentration and discrimination undermine it. When people are not given agency, they might assert it with protests and other forms of activism. For all these reasons, characterising, quantifying, and tracking agency is important.

A safe and just space

A just transformation of food systems should aim to keep everyone within a safe and just space. This is the space below the boundary that provides planetary stability and above the foundation that supports justice (shown in green in figure 10). However, the social harms associated with falling below the social foundations defined here are not evenly distributed, leaving far too many people with unmet human rights (to the left of the dashed vertical line in figure 10). Furthermore, people are not equally responsible for the extent to which the food system boundaries are already transgressed. Moving the global population to a safe and just space requires everyone to take reasonable responsibility for keeping food systems within planetary boundaries, by minimising the pressures they exert on the planet and by supporting efforts to ensure the benefits from food systems are distributed fairly and everyone's human rights can be met (figure 10).

Decisions regarding what constitutes reasonable responsibility for keeping the food system within planetary boundaries involve considerations of fair allocation. These decisions should be reached through deliberative processes that consider current capabilities and past responsibilities, including where lasting legacies (eg, colonial histories) continue to produce unjust outcomes for many marginalised communities. These processes could draw on existing principles and mechanisms that support equitable burden sharing in international processes and negotiations (eg, those used for climate change and trade deliberations), such as common but differentiated responsibilities and capabilities.[409]

Here, we apply the simplest principle as a starting point, which assigns each country an equal share of the planetary boundaries but makes no accommodation for differentiated capabilities or needs (eg, more efficient technologies).[409] For each country, and for four planetary boundaries where combined data are available (ie, control variables for GHG emissions, land use, water use, and nitrogen and phosphorus pollution), we calculate whether and how the food systems' share of the planetary boundary values would be exceeded if the dietary consumption patterns of that one nation were to be adopted globally. We compared these calculations with estimates of a country's distance from three social foundations, which had the most comprehensive data (ie, for diet affordability, agricultural wages, and nitrogen leaching; appendix 4 p 8). We used Kobe plots to visualise associations between the social foundations and planetary boundaries.

Currently, only 1% of the global population live in a country that is in the safe and just space. 74 countries representing 3·7 billion people (predominantly in LICs and LMICs in sub-Saharan Africa and south Asia) do not benefit from social foundations (ie, countries whose average foundation status is <100%). For these people, key barriers prevent their human rights from being met. At the same time, 144 countries representing 6·9 billion people (from all income groupings) transgress their share of the planetary boundaries (ie, countries whose average food system impact on planteary boundary status is >100%; figure 10). These are countries whose dietary patterns, if adopted globally, would transgress all planetary boundaries.

Policies that aim to secure social foundations should therefore ensure that changes to dietary patterns will not put disproportionate pressure on planetary boundaries. Efforts to support justice have not succeeded in protecting the planet, yet conditions that support a safe planet do not necessarily guarantee justice. Policies are therefore needed to simultaneously protect the planet and address justice, as almost every country in the world is currently outside (or on the edge) of a safe and just space. Countries least responsible for destabilising the planet fall the furthest below social foundations, whereas countries already exceeding their share of the planetary boundaries tend to also be the wealthiest, with the diets of the wealthiest top third of the global population (ie, from HICs and UMICs) amounting to more than 70% of the food systems' share of the planetary pressure.

Section 4: assessing potential environmental and socioeconomic consequences of a food systems transformation

To explore how food systems could become more aligned with health, environmental, and justice objectives, the potential consequences of their restructuring by dietary change, increased productivity, and reduced food loss and waste (FLW) should be assessed. We use two complementary modelling approaches for this purpose.

First, we assembled a multimodel ensemble of ten global economic models used in high-level assessments of climate change, land use, and food security,[410–415] and involved in the Agricultural Model Intercomparison and Improvement Project.[415–417] This

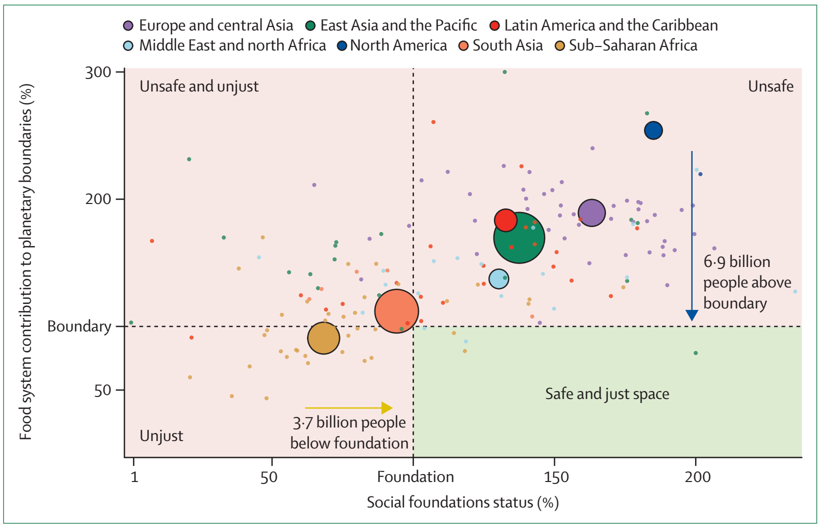


Figure 10: **Global population distribution among planetary boundaries and social foundations**
The Kobe plot compares each country's food system contribution to four planetary boundaries with their status of three social foundations. The y axis shows average contributions to greenhouse gas emissions, land use, nitrogen and phosphorus, and water use; 100% is the planetary boundary. The x axis shows average status for diet affordability, agricultural wages, and nitrogen exceedance to groundwater leaching, where 100% is the foundation. Large circles are regional averages, sized by total population. We estimated the total number of people in countries that fell below social foundations (3·7 billion people) or transgressed planetary boundaries (6·9 billion people). Countries above social foundations and below planetary boundaries would be in the safe and just space. Kobe plots comparing each social foundation and planetary boundary are available (appendix 4 p 15). Each country's social foundations status was normalised to have each social foundation equal 100%; countries either fall below (<100%) or above (>100%) the foundation. Values above the foundation were capped at a maximum of 300% to allow focused analysis on those below the foundation.

ensemble includes a mix of partial equilibrium models (focusing on the agricultural sector only), with more detailed biophysical and sectoral representation, and general equilibrium models (of the whole economy), which can simulate interactions across non-agricultural sectors (eg, energy). All simulate important system dynamics that would drive changes across a transforming food system, such as the ability of producers to substitute inputs based on their availability and cost.

Second, we used the Global Input–Output module of the Dietary Impact Assessment model (DIA-GIO), an updated version of the static input–output food model developed for the 2019 EAT–*Lancet* Commission (appendix 5 pp 30–32).[234] We used this model to improve our comparability with the modelling methods used in the 2019 Commission, recognising that economic systems might lack the capacity to adapt to rapid, large-scale changes. For example, delays to a food systems transformation would constrain the scope of food systems to adapt, hindering the possibility of efficiently reallocating resources across alternate uses, such as energy or fibre production. We therefore used DIA-GIO to assess a food system transformation without economic feedbacks, based on current and projected supply, demand, and trade relationships. Using DIA-GIO allowed us to consider the implications of a more constrained food system with more limited adaptation capacity than that suggested by the economic models.

See **Online** for appendix 5

The ways in which food systems can transform are not certain; as such, we used a range of models and modelling approaches to allow us to engage with this uncertainty. Here, we report ensemble median values and, where appropriate, full ensemble ranges (ie, minimum and maximum values), and compare these results to DIA-GIO. More detailed documentation on the models and modelling approaches applied in our analysis are provided in appendix 5 (pp 20–32).

Defining alternative future food systems

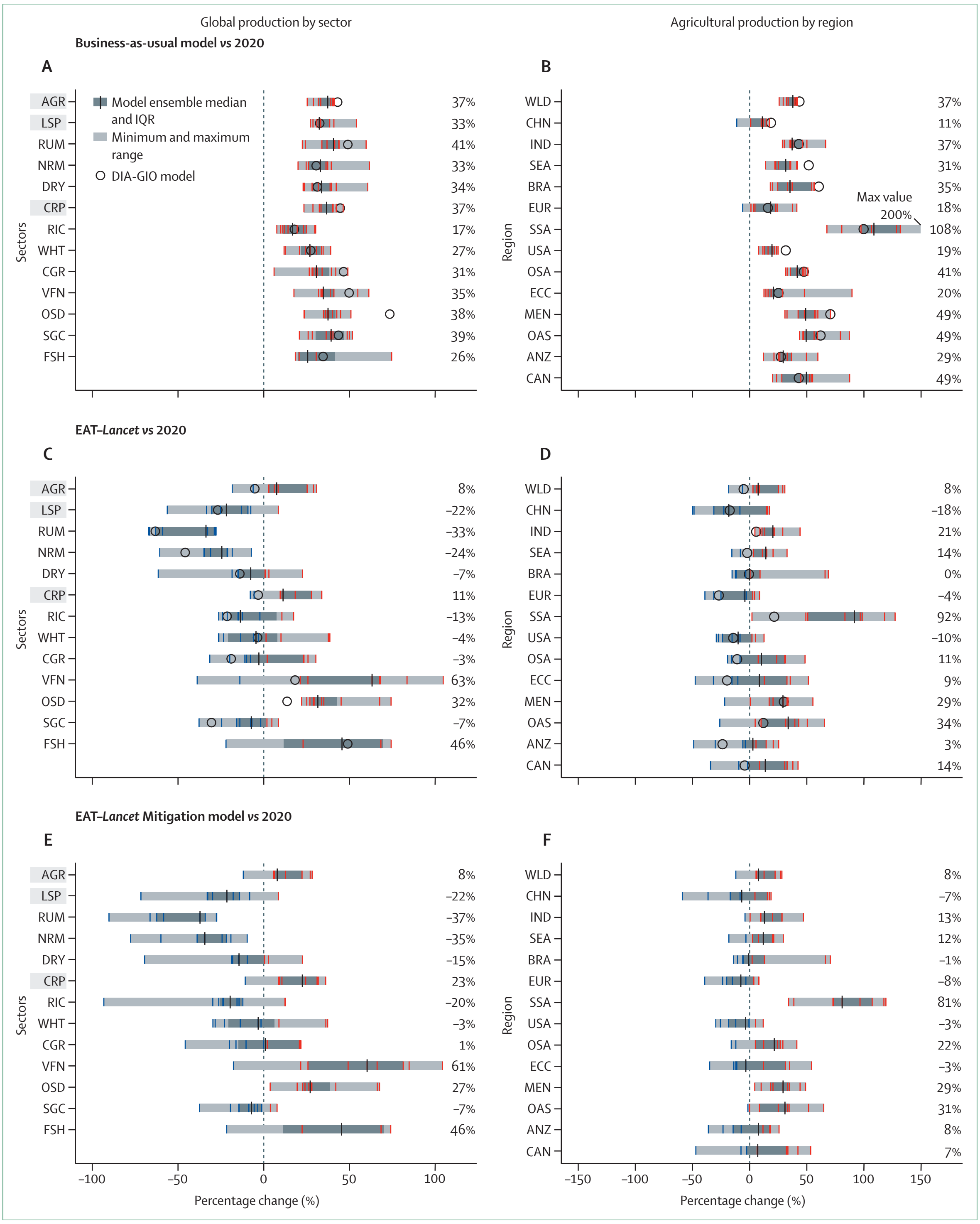
In addition to updating and extending the modelling suite, our analysis has updated the scenario framework used to assess global and regional changes across food systems. We constructed three core scenarios described in this section (appendix 5 pp 6–7).

The business-as-usual (BAU) scenario projects how food systems could look by 2050 assuming a continuation of current trends and policies. This scenario assumes population and economic growth based on the Shared Socioeconomic Pathways' middle-of-the-road scenario (SSP2), a scenario framework designed for the IPCC to model the consequences of climate change in the 21st century.[418–421] This scenario projects a global population growth of 23% to 9·6 billion people, and gross domestic product (GDP) growth of 127% to $282 trillion, between 2020 and 2050 (appendix 5 pp 14–16).[422–424] To simulate the consequences of climate change in the BAU, we applied a representative concentration pathway (RCP 7·0) that assumes minimal mitigation efforts and temperature increases of around 2°C by 2050. The biophysical consequences of this future climate were represented with the use of published estimated changes in crop yields,[425] livestock yields,[426] and agricultural labour productivity.[427] Following model parameterisation in the 2019 EAT–*Lancet* Commission,[1,234] DIA-GIO and BAU projections to 2050 were informed by projections from the International Model for Policy Analysis of Agricultural Commodities and Trade,[428] one of the participating global economic models.

Starting in 2020, the EAT–*Lancet* food systems transformation scenario deviates from the BAU scenario in three key dimensions. In the EAT–*Lancet* scenario, we assume that by 2050: (1) healthy diets will be adopted by all (table 1); (2) a 7–10% increase on top of global BAU agricultural productivity occurs, based on projections quantified as part of previous model intercomparisons[415,429] for SSP1,[415,429] a more sustainable shared socioeconomic pathway (appendix 5 p 16); and (3) food loss and waste in the BAU scenario is halved, consistent with Sustainable Development Goal 12.3. A final scenario, EAT–*Lancet* Mitigation (ELM), combines the EAT–*Lancet* scenario with ambitious mitigation, recognising that a shift to more sustainable food systems would be implausible without a wider societal transition towards greater sustainability.[412,415] Ambitious mitigation was based on previous modelling efforts to assess determinants of land use across SSP projections[415] and evaluate land-use policies and decarbonisation pathways to limit warming to 1·5°C by the end of the century.[412,415] Ambitious mitigation includes a range of policies (eg, emissions pricing and land-use regulations) that define market

***Figure 11:* Projecting 2050 agricultural production by sector and region**
(A) Global production by sector for the BAU scenario versus 2020. (B) Agricultural production by region for the BAU scenario versus 2020. (C) Global production by sector for the EAT–*Lancet* scenario versus 2020. (D) Agricultural production by region for the EAT–*Lancet* scenario versus 2020. (E) Global production by sector for the ELM scenario versus 2020. (F) Agricultural production by region for the ELM scenario versus 2020. All scenario results are reported as the percentage change between 2050 and 2020. Individual model results in the ensemble are given by vertical lines within the grey shadeds range (dark grey areas are IQRs; light grey areas are minimum and maximum ranges). Black vertical lines indicate median values, which are also expressed numerically in each figure. Results are coloured blue for a percentage decrease and red for a percentage increase. The DIA-GIO model results are given by the unfilled black circle and only include BAU and EAT–*Lancet* scenarios. Sectors are grouped by crop and livestock commodities. Aggregate sectors (ie, AGR, LSP, and CRP) are highlighted in light grey. Regions are ordered in terms of size of total agricultural production in 2020 based on data from the Food and Agriculture Organization of the UN.[430] BAU=business as usual. DIA-GIO=Global Input–Output module of the Dietary Impact Assessment model. AGR=all agricultural products (excluding FSH). CGR=coarse grains. CRP=all crops. DRY=dairy. FSH=fisheries and aquaculture. LSP=all livestock products (excluding FSH). NRM=non-ruminant meat products (ie, poultry, pork, and eggs). OSD=oilseeds. RIC=rice. RUM=ruminant meat. SGC=sugar crops. VFN=vegetables, fruits, and nuts (and legumes). WHT=wheat. ANZ=Australia and New Zealand. BRA=Brazil. CAN=Canada. CHN=China. ECC=Eastern Europe, Caucasus, and central Asia. EUR=Europe. IND=India. MEN=Middle East and north Africa. OAS=other Asia. OSA=other South and central America. SEA=southeast Asia. SSA=sub-Saharan Africa. WLD=world.

conditions that determine the technologies and practices adopted to maintain carbon budgets, such as afforestation, renewable energy, and bioenergy (see appendix 5 pp 8–13 and 28–29 for details on model specifications of ambitious mitigation). This scenario allowed us to assess potential synergies and trade-offs between a food systems transformation and ambitious economy-wide mitigation efforts, particularly through potential competition for land use. Although mitigation efforts would be expected to reduce climate impacts by the end of the 21st century, we use the climate impacts of the BAU (ie, RCP 7·0) in the EAT–*Lancet* Mitigation



scenario and recognise the uncertainty of these efforts translating to reductions in climate impacts by 2050.

We emphasise that these scenarios only aim to explore endpoints of a food systems transformation, and do not explore possible pathways that could lead to these outcomes by 2050. Assessing the implication of these endpoints is an important first step in understanding the potential benefits and costs of the changes simulated in these scenarios. Future work is needed to explore the pathways of change under varying assumptions of global development.

Comparing alternative food systems projections across modelling approaches

Across the model ensemble, the BAU scenario shows a 37% increase in global agricultural production by 2050 compared with 2020 (figure 11A). Livestock production increases by around 33%, and crops by 37%. All regions see increased overall agricultural production by 2050 compared with 2020 values, with the largest increases in sub-Saharan Africa (around 100%) and the smallest increases in China (11% for the model ensemble and 18% for DIA-GIO) and Europe (18% for the model ensemble and 16% for DIA-GIO; figure 11B).

Model results suggest that by 2050, the combined effects in an EAT–*Lancet* scenario could result in total agricultural production levels that are close to those reported in 2020, but with important changes in the composition of production (figure 11C). Compared with 2020, livestock production in this scenario declines by 22% (27% for DIA-GIO), which leads to a substantial reduction in the demand for and production of animal feed crops compared with BAU 2050. Although the models agree on the direction of change (ie, declining crop production compared with the BAU scenario), the magnitude of this reduction varies; some models suggest crop production levels in 2050 would be higher than those in 2020, whereas others suggest 2050 levels would be slightly lower.

A sectoral analysis of the EAT–*Lancet* scenario shows that the largest declines are in ruminant production (ie, cattle, goats, and sheep), with a 55% reduction (75% for DIA-GIO) compared with 2050 levels in the BAU scenario, or a 33% decline (63% for DIA-GIO) compared with 2020 levels across the ensemble (figure 11C; appendix 5 p 37). This reduction is accompanied by a decline in global ruminant animal numbers of 26% (ie, a result reported by the IMPACT and GLOBIOM models). Non-ruminant production had a smaller decline of 24% (a –46% change in DIA-GIO), with larger declines for pork (a –48% change based on three ensemble models reporting, and a –83% change in DIA-GIO) than poultry production (a –14% change for both DIA-GIO and the mean of two reporting ensemble models; appendix 5 p 37). The economic models generally show smaller declines in agricultural production compared with the DIA-GIO model, as other sectors (eg, pet food and industrial sectors) increase their demand for animal-based and plant-based products (appendix 5 p 43). Livestock demand for animal feeds declines in the EAT–*Lancet* scenario (–3%) from around 2·5 billion tonnes in 2020, to 2·4 billion tonnes by 2050. This reduction is especially notable compared with the BAU scenario, which predicts a 39% increase in feed production (to around 3·5 billion tonnes).

Changes in cereal production between ensemble models are varied, but the median results show modest production declines in rice (–13%), wheat (–4%), and coarse grains (ie, all other grains; –3%). Across the models, sugar crop production also declines compared with 2020 levels (–7% for ensemble and –30% for DIA-GIO).

The modelling approaches described here differ in their projections of production for vegetables, fruits, nuts and seeds, and legumes, primarily due to different commodity aggregations methods (VFN in figure 11). When we disaggregate these foods, we see much greater agreement between the ensemble and DIA-GIO, with vegetable production increasing by 42% (48% for DIA-GIO), fruit by 61% (36% for DIA-GIO), nuts by 172% (155% for DIA-GIO), and legumes by 187% (56% for DIA-GIO), with roots and tubers declining by 9% (–42% for DIA-GIO). The large variance in projected legume production can be attributed to ensemble models reporting soybeans (which account for the bulk of legume production) as oilseeds rather than as legumes, highlighting differences in how different disciplines (ie, nutrition *vs* agricultural economics) analyse food production and consumption. When we combine oilseeds and legumes across the ensemble, the median production by 2050 is 1·07 billion tonnes for the EAT–*Lancet* scenario across the model ensemble, compared with 1·08 billion for DIA-GIO.

If we consider a scenario with only increased productivity, the median projection for production across the ensemble is similar to the BAU scenario (39% for the ensemble *vs* 37% for BAU); however, the range of model projections is somewhat higher in the ensemble than in the BAU scenario (31–53% for the ensemble *vs* 25–41% for the BAU scenario; appendix 5 p 39). The use of global economic models highlights that, in isolation (and without dedicated policies), efficiency gains might not translate to lower overall production and could even increase it. Reducing FLW in isolation leads to a smaller increase in production of 30% (17% for DIA-GIO); similarly, dietary change on its own leads to only a 17% increase (18% for DIA-GIO) in agricultural production compared with 2020 levels (appendix 5 p 39). Reducing FLW achieves this smaller increase by shrinking the gap between what is consumed and what is purchased, signalling a need for less production to meet demand. A transition to healthier diets avoids overconsumption and reduces the demand for more resource-intensive, animal-sourced foods and animal feed.

Across livestock sectors, the ELM scenario shows larger declines in production compared with the EAT–*Lancet* scenario (figure 11E). Ruminant production in the ELM scenario declined by 37% (compared with 33% in the EAT–*Lancet* scenario); non-ruminant production by 35% (compared with 24%); and dairy production by 15% (compared with 7%). These larger reductions are the consequence of increased production costs from the pricing of emissions. However, ELM has slightly larger increases in crop production compared with the EAT–*Lancet* scenario, due to increased demand for crops from a growing bioeconomy (eg, for biofuels, biomass, and bioplastics) to facilitate a transition away from fossil fuels (figure 11E; appendix 5 p 43).

Exploring the biophysical option space of a food systems transformation

We estimated the consequences of an EAT–*Lancet* food systems transformation on the Earth system. Where possible, we align the control variables with the food system boundaries defined in Section 3 (ie, land, GHG, and blue water). However, where models cannot currently report against these variables (ie, for nitrogen surplus and phosphorus loss) we have used the control variables of nitrogen use and phosphorus use from the 2019 Commission as proxy indicators.

Our modelling results show that in the BAU scenario, the environmental impact of agricultural production is projected to increase by 2050 compared with 2020 levels. Agricultural production already exceeds the food systems' share of multiple planetary boundaries, with animal products being responsible for the majority of emissions, and grains for the majority of nitrogen, phosphorous, and water use (figure 12A). Agricultural emissions are expected to rise by 33% (20–50% for model range; 51% for DIA-GIO), primarily driven by a 22% (18–25% for model range) increase in ruminant animal numbers. The model ensemble projects agricultural crop yields to increase by 24% (17–46% for model range), which will slow—but not prevent—agricultural land expansion, which increases by 4% (1–7% for model range; 16% for DIA-GIO), or approximately 200 Mha, with cropland expanding by 10% (4–25% for model range). Model results show uncertainty around the potential of water-use efficiency gains and future irrigated area extent, with a median increase of blue water use of 13% by 2050, but with some models suggesting water use could decline (–10% to 43% for ensemble; 1% for DIA-GIO). By 2050, nitrogen application increases by 41% (22–55% for model range; 31% for DIA-GIO) compared with 2020 levels, and phosphorous application by 41% (36–46% for model range; 26% for DIA-GIO). This increase suggests that under a BAU future, food systems could exceed the resource-use boundaries by more than 100% for nitrogen use and by 55–75% for land, water, and phosphorous use (figure 12B).

All three components of the EAT–*Lancet* scenario (ie, dietary change, increased productivity, and reduced FLW) contribute to more efficient and less resource-intensive food systems by 2050. To achieve the agricultural emissions target of 5 Gt CO_2e per year from CH_4 and N_2O from biological processes, non-CO_2 emissions from agriculture would need to decrease by more than 30% from current estimates of 7·1 Gt CO_2e per year.[212] Under the EAT–*Lancet* scenario, and primarily due to fewer ruminants, agricultural non-CO_2 emissions decline by 20% (the ensemble median) and 32% (DIA-GO) compared with 2020 levels. However, agreement is low among models as to whether these reductions are sufficient to meet the food system boundary (ie, changes of –48% to 13% from 2020 levels, depending on the model). By 2050, all regions show emissions reductions in the EAT–*Lancet* scenario compared with the BAU scenario, with the largest decreases occurring in sub-Saharan Africa, Brazil, and the rest of Latin America (appendix 5 p 39). When the EAT–*Lancet* scenario is coupled with the emissions pricing and land-use policies of the ELM scenario, the model ensemble shows agricultural emissions declining further to 34% (–84% to –18% for model range) of 2020 levels, and below the food system boundary.

Ensemble results suggest that, in the EAT–*Lancet* scenario, total global agricultural land use (ie, cropland and grazing land) could fall by 7% (–26% to 1% for model range; a decrease of ~340 Mha) compared with 2020 levels, a substantial departure from the projections of the BAU scenario described earlier. Most of this decline comes from reductions in grazing land (–11%; –59% to 1% for model range). Latin America accounts for 30% of the decline in grazing land from 2020 levels (with Brazil alone accounting for 16%), and sub-Saharan Africa accounts for 22%. Such a reduction in future agricultural land use could provide room for conservation or restoration of natural ecosystems, particularly in these regions. The ensemble results project an 11% increase in cropland (–3% to 42% for model range) compared with 2020, whereas DIA-GIO suggests that cropland area could decrease by 22% (appendix 5 p 42). Coupling ambitious mitigation with a shift to healthy diets under the ELM scenario shows even greater reductions in future agricultural area, with agricultural land declining globally by 14% (–28 to –4% for model range) compared with 2020 levels. This larger reduction is due to both drivers reducing the demand for and production of animal products, especially of ruminants (the main users of grazing land).

Current estimates indicate that global blue water use remains below the food system boundary. However, regional water scarcity remains a major concern, and additional efforts might be needed to increase water-use efficiency and improve water management, particularly in areas already experiencing water stress (eg, the Indo-Gangetic Plain and the Mediterranean). The EAT–*Lancet* scenario reduces water use compared with the 2050 projections from the BAU scenario, but there is low agreement across the ensemble as to whether this

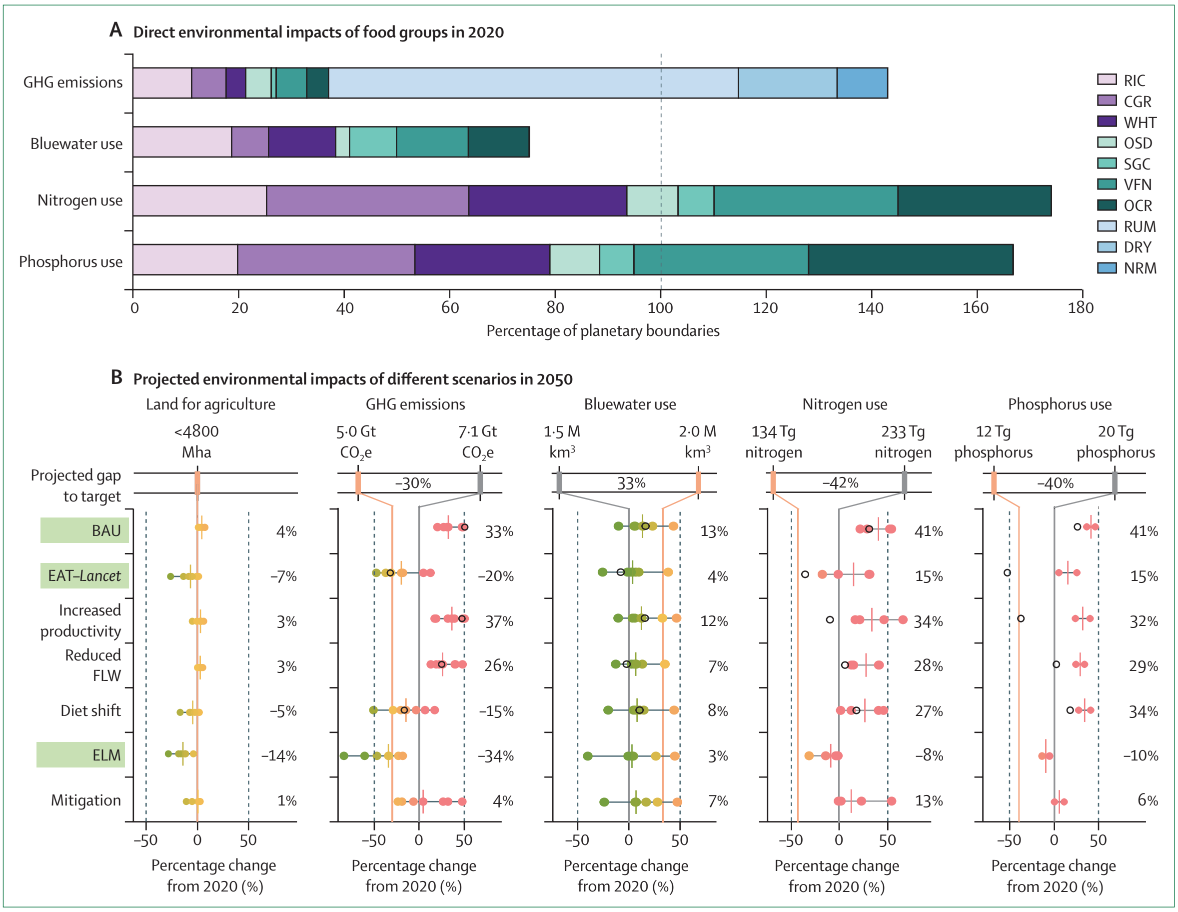


Figure 12: **Environmental impacts of food systems**

(A) Direct environmental contribution of food groups towards planetary boundaries in 2020. Nitrogen, phosphorus, and water use for animal feed production appear in crop production. Blue water is irrigation water. Rainfed crops do not impact the blue water boundary. Data are from DIA-GIO.[431] (B) Projected environmental impacts of different scenarios in 2050. The first row shows the current state (grey line) of the food system for five environmental variables—land for agriculture, non-CO_2 GHG emissions from agriculture, water withdrawals for crops, nitrogen use for crops, and phosphorus use for crops—and their food system boundaries (orange line). The percentage change needed from the current level to reach the boundary is indicated between the two lines. The lines continue from the first row and are translated to percentage change from the current state in the subsequent rows. Each subsequent row represents percentage changes relative to the current state for different scenarios in 2050: the core scenarios (highlighted in green) are BAU, EAT–*Lancet*, and ELM; their drivers are increased productivity, reduced FLW, diet shift, and climate mitigation. Vertical lines represent the multimodel median; lighter dots indicate individual model results. Colours indicate whether results are below (green), between (orange), or exceeding (red) the food system boundary. Open black circles indicate results from the DIA-GIO model. Dashed grey vertical lines mark the planetary boundary thresholds. BAU=business as usual. DIA-GO=Global Input–Output module of the Dietary Impact Assessment model. ELM=EAT–*Lancet* Mitigation. FLW=food loss and waste. GHG=greenhouse gas emissions. CGR=coarse grains. DRY=dairy. NRM=non-ruminant meat and byproducts. OCR=other crops. OSD=oilseeds. RIC=rice. RUM=ruminant meat. SGC=sugar crops. VFN=vegetables, fruits, nuts, and legumes. WHT=wheat.

reduction is sufficient to fall below 2020 levels (4%, –25% to 39% for model range; –8% for DIA-GIO). Ensemble results suggest similar blue water use by 2050 in the ELM scenario compared with the EAT–*Lancet* scenario (3%, –40% to 45% for model range), but with a wide range of outcomes. Under the EAT–*Lancet* scenario by 2050, nitrogen and phosphorous use decline compared with the BAU scenario; however, the planetary boundary remains transgressed as both nitrogen use (15%, –17% to 32% for model range) and phosphorous use (15%, 5% to 25% for model range) increase compared with 2020 levels. DIA-GIO results suggest that under the EAT–*Lancet* scenario, nitrogen and phosphorus inputs could decline substantially compared with current inputs (35% reduction in nitrogen and a 53% reduction in phosphorus). The difference between DIA-GIO and the economic models illustrates the potential for larger reductions in resource use if targeted measures are available to avoid rebound effects and reallocation of resources to other non-food uses.

Important complementarities exist across the three drivers of the EAT–*Lancet* scenario that, when combined, achieved better environmental outcomes than any individual driver in isolation.[432] Dietary change alone could substantially contribute to improvements in land and emissions boundaries; however, outcomes for water, nitrogen, and phosphorus use by 2050 varied due to rising demand for the many commodities that depend on these inputs. DIA-GIO showed greater environmental gains from increased productivity and reduced FLW compared with economic models, for which rebound effects in demand reduce the environmental gains from these drivers. For example, increased productivity in ruminant production lowers the cost of ruminant products, which in turn leads to lower consumer prices and stimulates increased consumer demand. This increase in demand leads to a larger ruminant herd, leading to similar emissions under the increased productivity scenario compared with the BAU results (figure 12B). A shift to healthy diets would avoid this outcome as it would reduce demand for ruminant products; however, it would also increase demand for perishable fruits and vegetables and could increase the volume of FLW, highlighting the increased importance of interventions to reduce FLW in an EAT–*Lancet* future.

The range of environmental results (ie, cropland extent, and blue water, nitrogen, and phosphorus use) highlights substantial uncertainty in how agrifood systems could respond to a food systems transformation. A transition to a healthy diet would include reductions in demand for some agricultural commodities (eg, animal-sourced foods and sugar), accompanied by a drop in intermediate demand from these sectors for inputs (eg, animal feed). However, this transition would also increase the demand for other agricultural commodities, such as fruits, vegetables, legumes, and nuts.

Various factors can affect whether a transition to a healthy diet would lead to a net reduction in resource use by agriculture. The first factor is whether resources dedicated to producing crops that are no longer demanded (eg, cropland, water, and fertilisers) can easily be converted and used to produce agricultural commodities that are growing in demand. For example, not all cropland dedicated to feed crops would be suitable (either climatically or economically) to produce fruits, vegetables, legumes, and nuts. The second factor is whether the crops increasing in demand are less resource-intensive than those that are declining in demand. Although animal-sourced foods are generally resource-intensive, so too are many of the crops increasing in demand (especially with respect to water and fertiliser use). Finally, many crops that are important for animal feeds (eg, cereals and oilseeds) are also inputs in various industrial uses (eg, cosmetics, bioplastics, and biofuels). Less demand for animal feeds would make these agricultural commodities cheaper, which could spur additional demand from outside the food system, reducing environmental gains. Models with larger reductions in resource use (eg, DIA-GIO) assume small rebounds in demand and fewer alternative uses for freed-up resources, whereas many of the economic models suggest that resources could have a wide range of other potential uses, which could lead to smaller environmental gains without additional policies (eg, land-use regulations or taxing environmental externalities) that encourage less aggregate resource use. Potential increased competition for resource use is more evident in the ELM scenario, which shows increased demand for agricultural products from the bioeconomy as part of the transition away from fossil fuels, and greater agricultural intensification on existing cropland due to restrictions on land expansion.

Together, these factors suggest that the changes modelled could contribute greatly to reducing environmental pressure. However, uncertainty remains with regard to whether these reductions fully place food systems within the safe operating spaces of planetary boundaries. Much of this uncertainty depends on how broad the scope is for alternative uses of natural resources and agricultural commodities, emphasising the need to couple supply-side and demand-side changes to avoid undesired consequences and rebound effects. The modelling results present an important foundation for a food systems transformation, and could be used as a guide for additional policies and innovations[433,434] that promote improved efficiency and resource use within the food system (eg, through precision agriculture, fertiliser management, or improved production allocation). Further reductions in FLW, applications of sustainable intensification approaches (panels 5, 6; figure 6; table 3; appendix 5 pp 12–19), or circularity[242,243,435] (panel 4; figure 5) might be required to return to a safe operating space.

Socioeconomic and justice implications of a food systems transformation

Assessing agricultural labour and livelihood implications

Changes in labour demand can have implications for production costs and income, and ultimately production and total demand.[436] Across all scenarios (ie, the BAU, EAT–*Lancet*, and ELM), assumed economic development and increasing urbanisation leads to an agricultural sector that contributes a smaller share of total economic output and employment by 2050.[437,438] Transitioning to a healthy diet (as in the EAT–*Lancet* scenario) with the projected effects on food production (figure 11) would have important consequences for the sectors that are increasing or decreasing their labour demands. Globally, we see modest additional reductions in agricultural demand for labour in the EAT–*Lancet* or ELM scenarios compared with the BAU scenario (figure 13A; appendix 5 pp 46–49). These results are consistent with recent DIA-GIO analyses using current sectoral and regional labour requirements, which found that shifting to a healthy diet could lead to a less labour-intensive global food system.[439] These results all suggest that transitioning to a healthy diet would not only be less resource intensive (as highlighted in the previous section), but also modestly less labour intensive to produce. The global

A

Region	2020	BAU	EAT–*Lancet*	ELM
ANZ	0·52 ··	0·44 (–14)	0·38 (–25)	0·39 (–24)
BRA	8·18 ··	5·53 (–32)	5·01 (–38)	4·96 (–39)
CAN	0·29 ··	0·24 (–17)	0·17 (–39)	0·20 (–31)
CHN	173·49 ··	85·33 (–50)	75·20 (–56)	75·15 (–56)
ECC	18·29 ··	11·43 (–37)	10·42 (–43)	10·66 (–41)
EUR	10·32 ··	6·04 (–41)	4·82 (–53)	5·02 (–51)
IND	214·27 ··	155·98 (–27)	162·64 (–24)	164·42 (–23)
MEN	23·55 ··	19·51 (–17)	18·02 (–23)	19·52 (–17)
OAS	63·55 ··	50·10 (–21)	48·66 (–23)	48·67 (–23)
OSA	29·75 ··	20·24 (–31)	18·39 (–38)	18·37 (–38)
SEA	107·06 ··	73·19 (–31)	74·34 (–30)	74·04 (–30)
SSA	214·52 ··	251·28 (17)	234·34 (9)	250·42 (16)
USA	2·70 ··	1·87 (–30)	1·63 (–39)	1·71 (–36)
WLD	866 ··	681 (–21)	654 (–24)	674 (–22)

Size of agricultural labour force (millions)

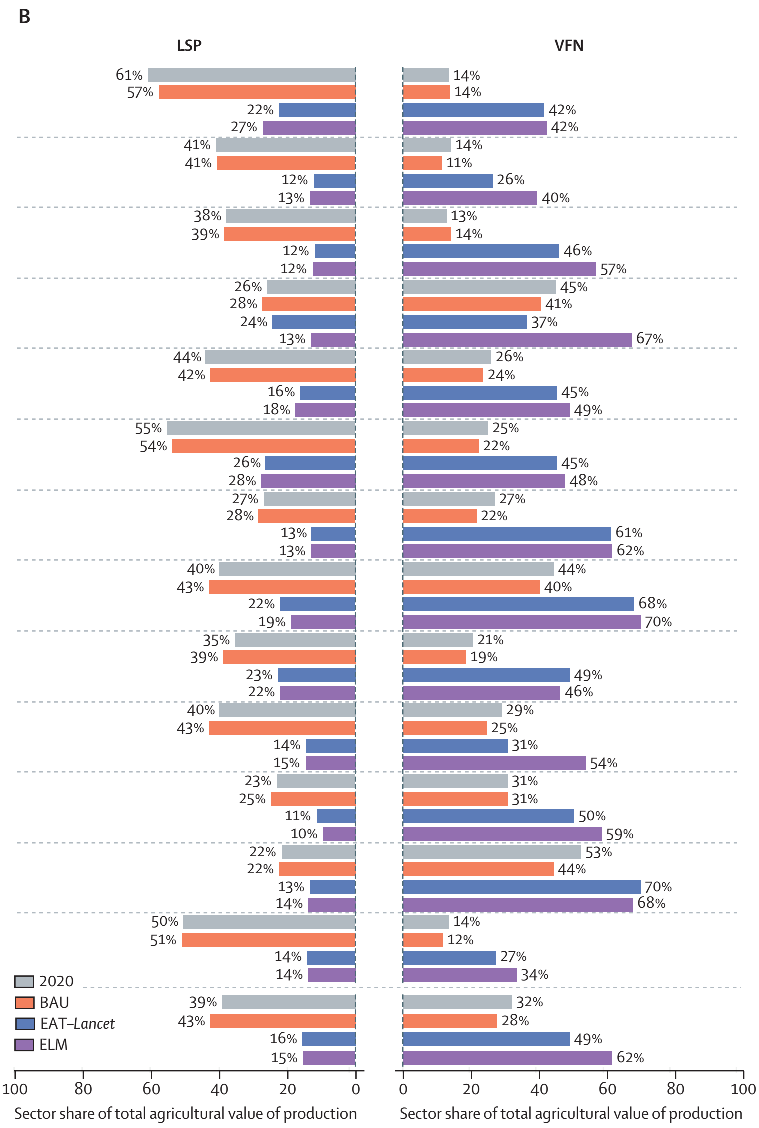


Figure 13: **Summary of regional disaggregation of agricultural labour and value of production**
(A) Agricultural labour force (millions) for the world and 13 regions by 2050 under BAU, EAT–*Lancet*, and ELM scenarios. Shading intensity reflects the regional share of global agricultural employment. Employment numbers are derived from benchmarking the percentage change (ie, 2050 *vs* 2020) of the median model to agricultural employment in 2020.[430] Percentage changes from 2020 by scenario are shown in parentheses. Full model results are available (appendix 5 pp 44–46). (B) The share of value for LSP and VFN within total agricultural value of production for 2020 (grey), BAU (red), EAT–*Lancet* (blue), and ELM (purple) scenarios. Agricultural value of production is given in current prices. BAU=business as usual. ELM=EAT–*Lancet* Mitigation. LSP=livestock production. VFN=vegetables, fruits, legumes, and nuts. ANZ=Australia and New Zealand. BRA=Brazil. CAN=Canada. CHN=China. ECC=Eastern Europe, Caucasus, and central Asia. EUR=Europe. IND=India. MEN=Middle East and north Africa. OAS=other Asia. OSA=other South and central America. SEA=southeast Asia. SSA=sub-Saharan Africa. WLD=world.

reduction in labour intensity is driven by various factors, including a reduction in the production of animal feeds and more labour-intensive animal sectors (eg, industrial pork, poultry, and dairy production), which would offset the increased labour demand from expanding crop production sectors (eg, for vegetables, fruits, and nuts).

Livestock sectors would face particular economic challenges from a shift to a healthy diet, with the livestock share of agricultural production declining from approximately 40% in 2020 (in dollar terms), to around 15% by 2050 in the EAT–*Lancet* and ELM scenarios (figure 13B). This reduction is due to the combined effect of a 41% decline in global production and a 31% decline in producer prices for livestock products (Gibson MF, unpublished), which contributes to a 36% reduction in livestock labour demand by 2050 compared with the BAU scenario. The increased demand for some plant-based foods—especially vegetables, fruits, and nuts—would drive increased demand for labour in these expanding sectors, which offsets most of the decline in livestock labour demand worldwide. These ensemble results are broadly consistent with DIA-GIO results, which suggest the shifts in sectoral demand for labour would result in a modest reduction in overall agricultural labour demand (<5%) globally.

The agricultural sector contributes a larger share of GDP and employment in low-income regions (<40%) compared with high-income regions (<5%).[440] Despite a decline in the contribution of agriculture to the economy compared with current levels, by 2050 agriculture would remain a large source of GDP and employment in many regions (eg, in India and sub-Saharan Africa). The sectoral demands for labour also vary substantially across regions and food systems. As such, the challenges of restructuring agricultural and food sectors vary regionally. Restructuring food systems could be more challenging in regions with large agricultural labour forces (eg, in India, sub-Saharan Africa, and China), or large livestock sectors (eg, Latin America). Regions with large vegetable, fruit, nut, and legume sectors (eg, China) could benefit from changes in demand without the need for substantial reallocation of resources across agricultural sectors. The sizes of agricultural labour forces by region, and the relative importance of livestock and vegetable, fruits, nuts, and legume sectors are shown to highlight regions where restructuring the demand for labour could be more challenging (figure 13).

Changes in labour demand would have consequences beyond aggregate employment levels, including on wages, but also on what jobs are needed, and how well they are remunerated. Model ensemble results suggest that agricultural wages could keep pace with the overall economy, with average agricultural wages increasing by 81% for BAU, 74% for EAT–*Lancet*, and 73% for ELM by 2050. However, substantial restructuring across agricultural sectors (ie, reductions in animal production and expansion of fruit and vegetable production) would have important justice implications. The model assumes a smooth transition to 2050 across all three scenarios; however, for such a transition to occur in the EAT–*Lancet* scenario, clear and consistent market signals would be needed to discourage new entrants (eg, producers newly entering a specific sector) into contracting sectors (ie, ruminants), while encouraging entry into expanding sectors (ie, vegetables, fruits, nuts, and legumes), along with the necessary investments in human and physical capital to facilitate labour transitions both within and outside of food systems.

Assessing production costs and food expenditure implications

Using various modelling approaches, we observe a smaller and less resource-intensive food system with the EAT–*Lancet* scenario compared with the BAU scenario. A food system aligned with the EAT–*Lancet* scenario would require fewer natural resources (ie, land and water), and less labour and chemical (ie, nitrogen and phosphorus) inputs. Across the ensemble, these changes could amount to a moderate reduction (8%) in average agricultural producer prices for the EAT–*Lancet* scenario by 2050 compared with the BAU scenario (figure 14A). Assuming current input requirements and prices, DIA-GIO projected a similar reduction in costs (10%). These modelling results suggest that, compared with the BAU scenario, transforming food systems by 2050 could produce healthy diets for all while also reducing input costs, natural resource use, and environmental pressures. However, whether this potential is realised will ultimately depend on the transition pathway (ie, the mix of policies, technologies, and cultural changes) followed to foster a food systems transformation that is compatible with the EAT–*Lancet* recommendations.

Across food systems, lower production costs could increase the average affordability of food if this reduction is passed on to consumers. However, lower producer prices can contribute to lower agricultural wages and income, with negative consequences on food affordability, particularly in rural areas. Ensemble results suggest that average agricultural prices would not change substantially from 2020 prices for both the BAU and the EAT–*Lancet* scenarios. However, in the ELM scenario, producer price

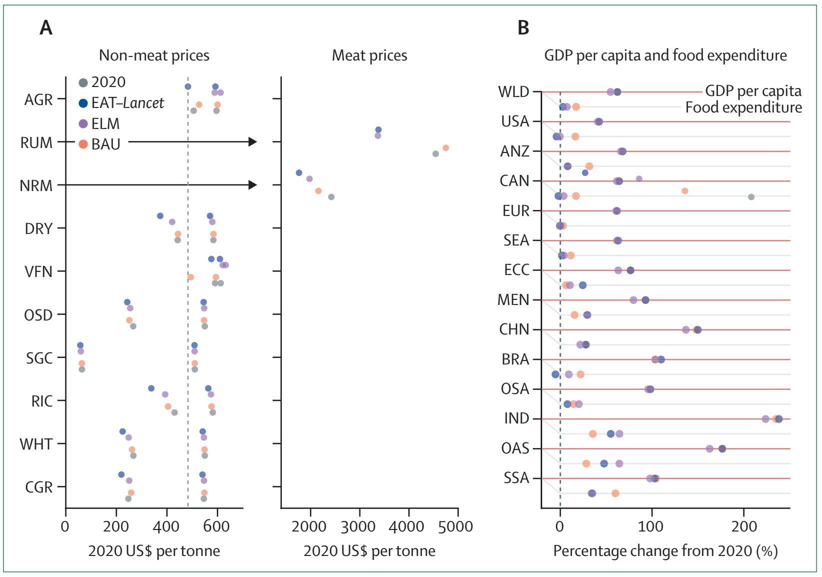


Figure 14: **Changes in agricultural producer prices and food expenditure implications**
(A) Global average prices by sector for 2020 (grey), the BAU scenario in 2050 (red), the EAT–*Lancet* scenario in 2050 (blue), and the ELM scenario in 2050 (purple). Global prices are expressed in 2020 US dollars per tonne (note the different scale for non-meat and meat prices). 2020 prices were obtained from the Food and Agriculture Organization of the UN.[430] Percentage change in prices (from 2020 to 2050) given by model results were applied to 2020 prices. (B) GDP per capita and food expenditure by region for BAU, EAT–*Lancet*, and ELM scenarios, expressed as a percentage change from 2020. Median GDP per capita for three reporting models (ie, AIM, ENVISAGE, and MAGNET) is located at the region's first row, followed by food expenditure results in the second row, which are expressed as percentage change from BAU 2020. BAU=business as usual. ELM=EAT–*Lancet* Mitigation. GDP=Gross Domestic Product. AGR=all agricultural products. CGR=coarse grains. DRY=dairy. NRM=non-ruminant products (ie, poultry, pork, and eggs). OSD=oilseeds. RIC=rice. RUM=ruminant meat. SGC=sugar crops. VFN=vegetables, fruits, nuts, and legumes. WHT=wheat. ANZ=Australia and New Zealand. BRA=Brazil. CAN=Canada. CHN=China. ECC=Eastern Europe, Caucasus, and central Asia. EUR=Europe. IND=India. MEN=Middle East and north Africa. OAS=other Asia. OSA=other South and central America. SEA=southeast Asia. SSA=sub-Saharan Africa. WLD=world.

increases by 2050 would contribute to a 10% increase in consumer prices compared with 2020. Food expenditure (reported by AIM, ENVISAGE, and MAGNET), which is a factor of consumer prices and food demand, is projected to grow in all three scenarios, but at a slower rate than per capita income, with the share of global income spent on food falling from 7% to 5% (for the BAU scenario), 4% (for the EAT–*Lancet* scenario), and 4% (for the ELM scenario) by 2050 (figure 14B). Globally, changes in food expenditure between the BAU and EAT–*Lancet* scenarios are driven by two offsetting shifts in a transition to a healthy diet. First, a decline in the demand for—and the prices of—animal-sourced foods, which are moderately more expensive than crop commodities. For example, by 2050 in the EAT–*Lancet* scenario, demand and producer prices for ruminant meat decline substantially compared with 2020 levels, even as ruminant prices remain substantially higher than prices of all other commodities (figure 14A). Second, demand for and prices of vegetables, fruits, nuts, and legumes increase substantially, which, at the global level, mostly offset decreased spending on animal products.

Although these two shifts mostly offset each other by 2050, some regions currently consuming low levels of animal-sourced foods (eg, India), or regions requiring large increases in demand for vegetables, fruits, nuts, and legumes (eg, eastern Europe, the Caucasus, and central Asia) to achieve a healthy diet, could see increased food expenditure in 2050 compared with the BAU scenario. By contrast, regions that are currently overconsuming animal-sourced foods (eg, the USA) could see declining food expenditures. This result is consistent with a recent analysis with DIA-GIO, which found that healthy diets could already be more affordable than unhealthy diets for individual consumers in HICs and UMICs, even as they remain more expensive in LICs and LMICs.[11]

Even as the share of income spent on food is declining for all regions and scenarios compared with 2020, the affordability of diverse healthy diets remains a concern. Low-income regions that import a substantial share of their vegetables, fruits, nuts, and legumes (eg, many countries in south Asia, central Asia, and the Pacific) could be especially vulnerable to international price shocks on domestic food affordability and availability. Furthermore, although food affordability is projected to improve in sub-Saharan Africa by 2050, the region continues to spend a larger share of income (21%) on food in the EAT–*Lancet* scenario than any other region. These regional results suggest that low-income regions (listed at the bottom of figure 14B) could remain vulnerable to food poverty, and that targeted interventions to account for higher prices of vegetables, fruits, nuts, and legumes, and social protections to ensure consumers can afford a healthy diet, might be needed.

These results highlight that a food systems transformation, if achieved, could contribute towards social and environmental goals. However, the mechanisms for this transformation (eg, taxes, repurposing of subsidies, and true cost accounting approaches) will be essential for informing and incentivising behaviour change towards more sustainable

Panel 9: Understanding the drivers of price changes to inform policy priorities

To assess which scenario drivers (ie, dietary change, increased productivity, reduced food loss and waste [FLW], and ambitious mitigation) were most responsible for changes in agricultural prices, we conducted a decomposition analysis using four models from the ensemble (ie, AIM, CAPRI, ENVISAGE, and MAGNET) that reported regional consumer and producer (eg, farm gate) prices (see appendix 5 pp 41–43 for full ensemble results of producer prices).

Ambitious mitigation could increase the cost of production in all regions by restricting agricultural land expansion and pricing emissions. However, increased producer prices translate to higher consumer prices, posing a risk to food security. Dietary change has a more varied effect on prices: in Brazil and the USA (regions with a high consumption of animal-sourced foods), adoption of healthy diets could reduce average consumer prices by 7% (in Brazil) and 4% (in the USA; figure 15G and 15H, yellow bar). However, in India, where red meat consumption is low, increased demand for vegetables, fruits, nuts, and legumes could contribute to a 10% increase in average consumer prices (figure 15E, yellow bar).

Increased productivity and reduced FLW contribute to more efficient food systems, reducing the cost of production and leading to lower consumer prices in all regions. The potential to mitigate price increases is particularly important in low-income regions with greater food security challenges. For example, in India and sub-Saharan Africa, reduced FLW and increased productivity partly offset price increases due to ambitious mitigation and dietary change (red and blue bars of figure 15). FLW reductions contribute more to reductions in consumer prices than producer prices, with the biggest gains being in regions with high levels of consumer waste (eg, in the USA; figure 15B and 15H). These results suggest the importance of supply-side interventions that increase the efficiency of food systems, particularly in low-income settings where price rises pose immediate food security risks.

Previous modelling[441–444] has suggested supply-side measures (ie, investments in resource-use efficiency, agricultural research and development, and improved extension services) would be insufficient to alleviate food insecurity. As such, policies and interventions that improve infrastructure and functioning of markets, as well as demand-side interventions such as price subsidies and poverty alleviation measures, would be needed to manage higher diet costs in low-income regions.

production practices and healthier consumption patterns. The cost of these actions will ultimately determine whether a food systems transformation increases or decreases the cost of individual foods and the overall diet.

Mitigation efforts (appendix 5 p 40) could increase the cost of agricultural production by restricting land supply and pricing emissions. Across the ensemble, mitigation efforts in isolation would increase consumer prices by 17% (0–40% for model range) compared with 2050 prices in the BAU scenario. This price projection is broadly consistent with past studies, suggesting that mitigation efforts could increase food prices.[414] This increased risk is due to multiple factors that raise the price of producing and consuming food. First, mitigation and land-use policies increase the cost of key agricultural inputs (eg, land and fertilisers), which raises the cost of production. Second, emissions pricing raises the cost of agricultural products, particularly of emission-intensive commodities (eg, ruminant meat). Vulnerability to food pricing changes varies, with low-income regions (eg, sub-Saharan Africa) already at heightened risk of food insecurity being the most vulnerable to price increases. Exactly how components of the EAT–*Lancet* scenario contribute to changes in producer and consumer prices, and their potential policy implications, are explored in panel 9 and figure 15.

Low-income and middle-income regions (eg, China, Brazil, and sub-Saharan Africa) are responsible for the largest reductions in emissions and agricultural land use in the EAT–*Lancet* and ELM scenarios, and are regions at greater risk of increased food prices as a result of dietary change. Historically, these are also the regions that have recently observed large changes in land use and have had the least access to novel technologies and affordable, reliable energy. These regional inequalities highlight the importance of increasing productivity to reduce agricultural yield gaps, and of reducing FLW, both of which could have important roles in alleviating price pressures caused by a shift to healthy diets or ambitious mitigation (or both). Potential complementarities exist between a transition to a healthy diet and ambitious mitigation: both alleviate land-use pressure and reduce consumption of GHG-intensive foods. Further demand-side interventions could also help in managing food affordability concerns. Previous modelling suggests that targeted food subsidies, bundled with mitigation policies[445,446] or full cost efforts (which try to cost negative and environmental externalities),[447] could help to manage these price increases, as discussed in the following section.

Section 5: solutions and actions to improve health, environmental sustainability, and justice

A great food transformation[1] is required if the world is to align with the EAT–*Lancet*'s vision by 2050. This transformation must operate across multiple leverage points, including profound shifts in the underlying objectives of food systems outcomes.[448,449] The focus should move beyond simply maximising profit and volume in

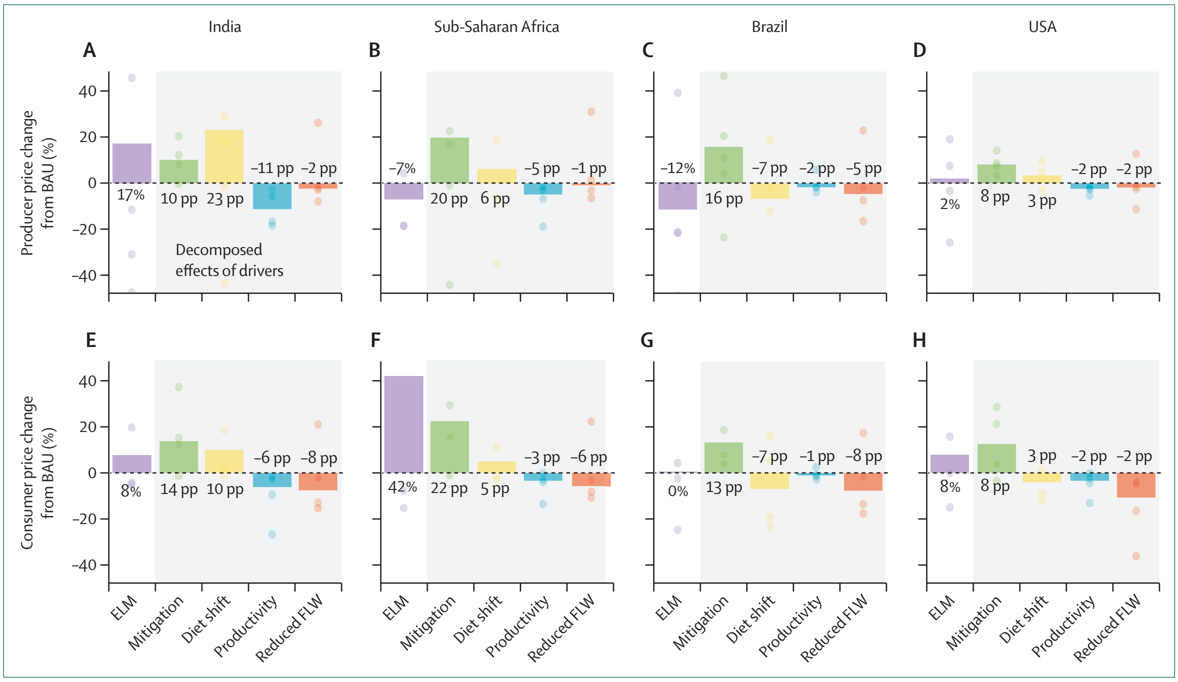
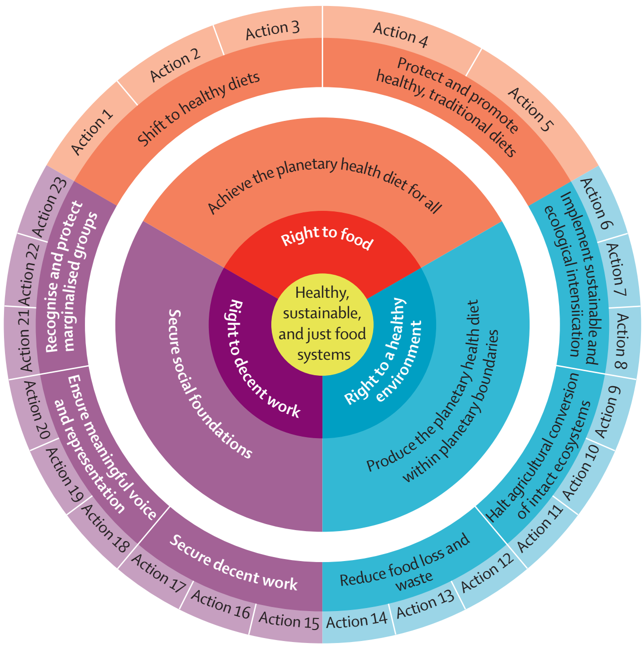
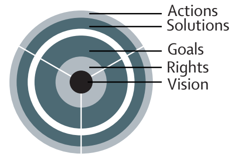


Figure 15: **The key drivers of price changes in the ELM scenario**

Regional impact of the ELM scenario (purple) on producer (A–D) and consumer (E–H) prices as percentage changes (%) from the BLM scenario, decomposed into four key drivers shown as percentage points: mitigation (green), diet shift (yellow), increased productivity (blue), and reduced FLW (red). Note that decomposition values are not additive due to the interactions between the four scenario drivers (see appendix 5 p 19 for an explanation of decomposition). BAU=business as usual. ELM=EAT–*Lancet* Mitigation. FLW=food loss and waste. PP=percentage points.





Effect of action on intersecting goals:
- Potential large postive impact (Large)
- Potential positive impact (Positive)

Solution		Action	Health	Environment	Justice
1 Shift to healthy diets	1	Use taxes and subsidies to shift affordability of unhealthier foods towards the affordability of healthier foods	Large	Large	Positive
	2	Combine advertisement restrictions with mandatory warning labels on unhealthy foods	Large	Large	Positive
	3	Increase purchasing power for households in the lowest quintile through different social protection measures	Large	Large	Large
2 Protect and promote healthy, traditional diets	4	Recognise and include traditional healthy foods and diets in food-based dietary guidelines and public procurement programmes (eg, school meal programmes)	Large	Large	Large
	5	Support local markets, including the development of value chains, to promote consumer demand of underused, healthy, and locally produced crops	Large	Large	Large
3 Implement sustainable and ecological intensification	6	Ensure producers have access to enhanced governance over land, sea, production inputs, agricultural training and extension, peer-knowledge networks, and markets	Positive	Large	Large
	7	Mitigate power imbalances between producers and corporations by supporting producer coalitions, introducing subsidies for sustainable practices, and regulating corporate control, global trade, and financialisation	Positive	Large	Large
	8	Increase public and private sector investments to cover the transition costs, research, and development processes of sustainable and ecological intensification practices	Positive	Large	Large
4 Halt agricultural conversion of intact ecosystems	9	Combine regulatory measures, such as protection of natural ecosystems, suspension of logging concessions, and implementation of land-use zoning, with coordination mechanisms to reduce land expansion leakage	Positive	Large	Positive
	10	Invest in community management of local ecosystems, including Indigenous communities, to promote stewardship of land and water, and balance conservation and use of ecosystems	Positive	Large	Large
	11	Increase multisector commitments to zero-deforestation commitments across supply chains	Positive	Large	Positive
5 Reduce food loss and waste		Use fiscal and regulatory policy incentives, as well as circular economy mechanisms and technologies, to:			
	12	Improve storage, logistics, and supply chain data and analytics, especially in low-income settings	Positive	Large	Large
	13	Reduce retail and consumer waste through improved awareness, education, and skills, especially in high-income settings	Positive	Large	Positive
	14	Recycle nutrients and energy, prioritising animal feed and on-farm waste recovery	Positive	Large	Positive
6 Secure decent work	15	Guarantee payment of updated living wages for all and close the gender pay gap	Large	Positive	Large
	16	Provide training in skills that can enhance redeployment in the context of a food systems transition (especially for youth, women, and the current labour force)	Positive	Positive	Large
	17	Improve enforcement of legislation, in society in general and food system workplace specifically, against: • Gender-based violence and sexual harassment • Occupational health conditions • Child labour	Positive	Positive	Large
7 Ensure meaningful voice and representation	18	Ensure the existence of enabling mechanisms for collective bargaining by agrifood system workers and farmers	Positive	Positive	Large
	19	Develop legal and regulatory frameworks to limit market concentration and ensure transparency in lobbying	Large	Large	Large
	20	Improve transparency, accountability, representation, and access to information through, supporting civil society, enabling social audits to hold actors accountable, and increasing women's representation in positions of influence	Positive	Positive	Large
8 Recognise and protect marginalised groups	21	Implement a range of social protection policies that can provide benefits for those at risk, including mothers, people with low income, older people, and disabled people	Large	Positive	Large
	22	Procure and implement healthy and sustainable meals in schools and other institutions	Large	Large	Large
	23	Protect basic human rights of people in conflict areas	Large	Positive	Large

***Figure 16:* Goals, solutions, and actions to achieve healthy, sustainable, and just food systems**
Depending on how they are implemented, all actions have the potential to contribute positively to other goals. The suggested strength of positive impact was developed based on dialogue with the Commissioners.

agriculture, to achieving food security in ways that prioritise diet quality and advance health, sustainability, and social justice. Equally essential are interventions that change underlying rules and incentives of the food system, such as taxes, subsidies, and regulations,[448,449] as these form the conditions under which deeper shifts in values, norms, and governance can emerge.

This section focuses on these underlying rules and incentives through the lens of eight domain-specific solutions aimed at advancing health, environment, and justice goals simultaneously. For every solution, we identify two to three actions that the Commission has evaluated, based on a review of existing literature, as being essential for transforming food systems. These actions are grounded in available scientific evidence to highlight their potential in delivering meaningful impacts across health, environment, and justice outcomes, and also in creating the enabling environment for more profound systems change. These solutions and their associated actions are summarised in figure 16.

Several analyses have shown that individual policies and interventions, on their own, are insufficient to drive multi-goal transformative change. Instead, bundled or integrated approaches are needed—for example, to keep global warming below 1·5°C[450] or to reduce the hidden costs of current food systems (estimated to be $15 trillion per year)[12]—because the drivers and outcomes of food systems are highly interconnected and interact in direct and indirect ways.[451] Investing in coordinated sets or packages of solutions is therefore essential to positively transform food systems.

We highlight some of these dynamics in actions 3 and 15–23. The domain-specific actions presented in this section are not isolated; rather, they are deeply interconnected and can produce synergistic effects across goals, while also navigating potential trade-offs. For example, introducing regulations to limit land-use expansion might promote health and environmental sustainability, but could risk undermining justice if these limitations restrict marginalised or Indigenous communities' access to that land. However, if such regulations are implemented alongside efforts that recognise and protect the resource use of these groups, both sustainability and justice can be enhanced. By implementing actions as part of carefully designed bundles, multiple goals can be advanced simultaneously.

Goal 1: achieve the planetary health diet for all

Solution 1: shift to healthy diets

To shift diets towards the PHD, it should ideally be more available, affordable, convenient, aspirational, appealing, and delicious than unhealthy alternatives. Two sets of feasible interventions emerged from a scoping review of systematic reviews.[452] Both sets of interventions focus on food environments—the physical, economic, political, and sociocultural settings in which people engage with the food system to acquire food[453]—and are considered to be more cost effective and equitable than interventions targeting individuals or households.[453–455] The first set includes price-based interventions, which are likely to reduce the purchase and consumption of unhealthy foods.[456–458] The second set involves non-price-based interventions that restrict advertising and availability of unhealthy foods and mandate the use of warning labels to discourage consumption.

Taxes on foods and beverages with high amounts of added sugar, salt, or saturated fats (or a combination thereof) are particularly effective when combined with subsidies on nutritious foods that decrease their relative price.[458,459] Modelling studies suggest optimal price levels for mitigating health and environmental impacts of unhealthy foods and meat, which would require calibration by context.[445,446] By contrast, restricting advertising and marketing of unhealthy foods could shift populations towards healthier foods.[460,461] Labelling foods to denote those that are high in calories, fat, sugar, and salt reduces purchasing and consumption.[462,463] This intervention can be achieved through the use of mandatory, front-of-pack warning labels as in several Latin American countries (eg, Chile and Mexico), or through traffic-light systems as is common in Europe.[464] Reducing the proportion of unhealthy foods that are available in the market, in parallel with increasing the proportion of healthier foods,[465,466] can reduce purchasing and consumption, as can reducing the portion, package, and serving sizes of energy-dense, unhealthier foods.[467,468]

The affordability of food is determined by supply and demand dynamics, and by purchasing power.[11,352] When making the PHD affordable for all, increasing purchasing power for consumers with low incomes is more important than reducing the price of foods.[469] Social protection measures, including the provision of nutritious school meals (panel 10), public procurement and distribution systems, employment guarantee schemes, and government investments in health-promoting insurance systems, all have the potential to contribute to increased affordability for low-income households. Living wages, universal basic income, income growth, and government welfare systems, especially for economically disadvantaged people,[477] and more equitable distribution of the benefits of national economic growth through fiscal policies, would also support increased purchasing power. Previous modelling studies suggest that the relative cost of a healthy diet can be substantially reduced—even in LMICs—through combinations of pro-poor income growth (ie, strategies aiming to support income growth in low-income households through tax exemptions, lower tax brackets, and minimum wage bands), reduced FLW, and true cost accounting approaches that consider the effects of diet on climate and health.[11]

Solution 2: protect and promote healthy, traditional diets

In some regions, traditional diets are closely aligned with the principles of the PHD.[75,478,479] Although not all

Panel 10: School meals

School meals are increasingly recognised as a cost-efficient investment for governments to advance multiple policy objectives, including health and nutrition, education, social protection, and agriculture.[470] Well designed and strategically implemented school meal programmes within 7000 days—the period of development between the first 1000 days of life and adulthood—can have a profoundly positive effect, particularly on the most vulnerable children and adolescents, by improving attendance and academic performance, and reducing dropout rates.[471]

School meal programmes are one of the largest outputs of the global food system, feeding 420 million children daily. Sustainable school meals, coupled with consistent and action-oriented food education, can empower future generations by fostering healthier and more sustainable food habits at an age where lifelong dietary preferences and social attitudes are formed and carried into adulthood.

In 2021, in recognition of the unique potential of school meals for improving child health, wellbeing, and education following the COVID-19 pandemic, national governments formed the global School Meals Coalition, declaring their commitment to scaling up and strengthening their national school meal programmes to ensure every child has access to a nutritious meal at school by 2030. To support the 105 member states of the School Meals Coalition in achieving this ambitious mission, the independent Research Consortium for School Health and Nutrition, with the input of 160 global experts from more than 80 organisations, identified evidence-based policy approaches to support the delivery of diverse, balanced, and sustainably produced school meals.

As these programmes are overwhelmingly domestically financed and managed, policy components are controlled by national governments, allowing for notable change to be made at pace. Incorporating sustainable school meal policies can reduce environmental impacts, improve climate resilience, and leverage food systems transformation in both high-income and low-income settings. Key policy strategies to support positive change in this area include providing nutrient-rich menus that are predominantly plant-based; sourcing production from local farms using sustainable and ecological intensification practices that support agrobiodiversity and climate resilience, as well as structured demand and stable markets to smallholder farmers and processors; shifting to efficient cooking solutions to reduce negative health and environmental effects; reducing food loss and waste; and ensuring action-oriented food and climate education to enable future generations to make sustainable choices. With increased awareness, children also serve as powerful agents of change within their families and broader communities.[472]

Countries and regional bodies are already showing that these actions are possible. The EU now requires a minimum share of organic foods in school menus,[473] and approximately 40% of national school meal programmes have agriculture policy objectives such as agrobiodiversity, food sovereignty, and the inclusion of climate-smart foods.[474] The national school meal programme in Brazil legislates that at least 30% of the food used in the preparation of school meals is locally sourced from family farms.[475] Many countries in Africa and Asia have also implemented a food systems approach to school meals, often involving public–private partnerships.

Although financing is often the barrier to scaling up, food-related costs of providing healthy and sustainable school meals to every child could amount to up to 1% of gross domestic product in low-income countries, in which school meal coverage is low.[476] Given the long-term costs of inaction—such as the treatment of diet-related health issues and the impact of greenhouse gas emissions—the case for investing in school meals becomes undeniably compelling. The study[476] identified savings of $120 billion to $200 billion in treating diet-related illnesses (including $7 billion to $13 billion in low-income countries), and a reduction in costs associated with climate change of $18 billion to $70 billion (including $1 billion to $5 billion in low-income countries). The savings were greatest, in each case, for meal compositions in line with recommendations for healthy and sustainable dietary patterns.

In summary, sustainable school meal policies can positively influence dietary preferences of the next generation, promote the adoption of sustainable production practices, broaden diets, and stimulate crop diversity, along with other social and economic development outcomes. The inclusion of school meals on the climate finance agenda, as well as in Nationally Determined Contributions for both health and the environment, are important steps towards building more resilient, sustainable, and equitable food systems.

traditional diets are inherently healthy or sustainable in their current form, they frequently embody a deep connection to the local environment, biological diversity, agricultural practices, cultural beliefs, and long-standing adaptations to available resources.[191,480] However, revitalising traditional diets is challenging. Efforts such as the promotion of millets in India and anchovetas in Peru illustrate the difficulty and resistance such initiatives can face, often due to opposition from entrenched commercial or political interests.[481] Amid ongoing nutrition transitions and the rapid rise in the supply and demand of ultra-processed foods, healthy and traditional dietary patterns that are at risk of erosion should be identified, promoted, and protected.[188]

Various approaches exist that recognise and enhance the cultural, environmental, and nutritional value of Indigenous and traditional diets. These approaches aim to make such diets more desirable, accessible, and affordable.[190,482] Cultural valorisation, including the celebration of traditional foods, can elevate their social status and render them more aspirational.[190] For example, the Food and Agriculture Organization of the UN's designation of the International Year of Millets in 2023 sought to raise awareness of the environmental, climate resilience, and health benefits associated with these crops.[483] Incorporating traditional, healthy foods into national food-based dietary guidelines and nutrition education programmes can help safeguard local knowledge and culinary practices.[482] Moreover, linking these efforts to public procurement policies—such as school feeding programmes—and social protection schemes can magnify their reach and impact.

Public investment in local and territorial markets can further strengthen value chains and stimulate demand for underused, nutritious, and locally produced foods.[484–487] Similarly, the development and support of local seed systems can have an important role in preserving and scaling up agrobiodiversity, particularly for underconsumed fruits, nuts, legumes. and vegetables.[488] These crops have often been displaced by dominant staples such as wheat and rice, but offer climate-resilient and nutritional benefits, and merit renewed attention.[489]

Goal 2: produce the planetary health diet within planetary boundaries

Solution 3: implement sustainable and ecological intensification

In regions charactirised by substantial yield gaps, policies aimed at increasing productivity through SEI practices can increase resource-use efficiency by reducing the environmental impact of production per unit.[490] Conversely, in areas where agricultural productivity is already high, policy efforts should prioritise reducing environmental degradation and pollution associated with intensive farming systems and practices (see section Reducing the environmental footprint of food production).

Securing long-term access to land and water resources is essential for enabling farmers to adopt and implement SEI practices—many of which need substantial upfront costs or require more time to yield benefits—particularly when used to rehabilitate or recover exhausted or degraded lands.[491] Access to land is especially important for women, who frequently face additional and entrenched legal and sociocultural barriers to ownership and control.[492] Despite their pivotal role in supporting marginal groups and remote communities, public advisory (extension) services have suffered from chronic underfunding.[493] Revitalising and redesigning these services, with coordinated support from public, private, and civil society actors, is essential to assist farmers in transitioning and adopting new methods towards sustainable practices.[493] Strategic investments in farmer networks—through facilitating knowledge exchange, equipment sharing, and improved market access—can also reduce barriers to adoption. Brazil's success in promoting diversified and organic farming through the integration of farmer networks with supportive public policies is a notable example of such investment.[494]

Addressing the structural imbalances between producers and dominant agricultural corporations is essential. Strengthening anti-trust legislation and implementing policies to reduce excessive market concentration can reduce systemic barriers to SEI adoption and practices.[494] Robust competition policies can foster more equitable pricing for producers, support diversified market structures, and stimulate innovation,[20] all while contributing to the resilience of food systems.[495,496] In parallel, tighter regulation of food commodity speculation could stabilise producer incomes and create more favourable conditions for long-term investments.[497]

Both public and private sector investments are needed to support the transition to SEI practices, particularly in offsetting the initial costs of advancing the research and development of innovations and appropriate technologies.[498] Investing in labour-saving technologies can reduce the burden of otherwise labour-intensive practices, and breeding high-yield, climate-resilient crop varieties that are suited to conditions with low chemical input can improve the productivity and profitability for SEI practices. Financial mechanisms such as payments for ecosystem services[499] and cost-share payments[494] can provide crucial support to farmers adopting more sustainable practices. Historically, most agricultural subsidies have been directed towards a narrow set of staple crops—wheat, rice, maize, soy (for animal feed), and dairy.[490] To realign agricultural production with dietary recommendations that emphasise increased consumption of legumes, nuts, fruits, and vegetables, subsidies should be reformed.[500] Targeted investment in under-supported foods, alongside research to improve their yield, resilience, and regional adaptability, is essential to building more sustainable, health-promoting agricultural systems.

Solution 4: halt agricultural conversion of intact ecosystems

Multimodel ensemble results indicate that, by 2050, agricultural land will decline by 7% compared with 2020 levels, as a result of dietary shifts, increased agricultural productivity, and reductions in FLW. However, to restrict the expansion of agriculture and aquatic systems into intact systems, a combination of regulatory policies, community management, and multisectoral commitments and coordination is necessary. This combination could include the strict protection of natural ecosystems, and the suspension or restriction of logging concessions and commercial fishing licenses in protected areas. These regulations should be implemented in ways that minimise leakage (ie, ensuring that the protection of land and water in one region does not inadvertently result in increased exploitation elsewhere).[501] Attention should be given to populations inhabiting or using resources in protected areas by ensuring meaningful stakeholder engagement and, where appropriate, empowering leadership by Indigenous communities.[502] Recognising and securing land and sea tenure rights for these communities is essential. Retaining biodiversity intactness can also be compatible with certain forms of sustainable land and water use, such as wild harvesting, selective logging with native species, or extensive rangeland management that maintains native biodiversity. In such cases, sustainable uses are those that are well below the 10% HANPP threshold (table 2), and those for which the biodiversity intactness index values remain above 95, thereby minimising their impact on species composition.[200]

Both regional policies and voluntary initiatives in the EU and the UK have introduced zero-deforestation commitments across supply chains.[503] Although some region-specific and commodity-specific commitments have contributed to small reductions in deforestation,[504] the evidence of effectiveness of these efforts is scarce, as they are still understudied and fairly new.[505,506] However, these initiatives have spurred progress in monitoring, traceability, and awareness of deforestation, and expanding their implementation to cover a larger share of the market could greatly increase their impact on global deforestation reduction.[506]

Solution 5: reduce food loss and waste

The ensemble scenario results indicate that halving FLW, in alignment with Sustainable Development Goal 12.3, yields moderate benefits across all five modelled planetary boundaries. Some level of loss or waste is inevitable for food safety and reliability of supply; however, FLW can be reduced (to lower demand for food production) or recycled into the circular economy (panel 4). The food waste pyramid[507] outlines a hierarchy of recycling management options based on financial and environmental returns. Depending on the context, the highest priority is usually to feed waste to livestock (although livestock numbers are reduced in one of the EAT–*Lancet* scenarios), followed by industrial uses—including anaerobic digestion for biogas and other products—then composting, incineration, and, finally, landfill disposal.

In low-income contexts, food loss mainly occurs at the production and post-harvest stages, whereas in high-income contexts, consumer-level food waste is the main contributor.[508] Reducing food loss depends on improving storage, transportation logistics, and access to labour and equipment to ensure timely harvests and transformation of crops into sought-after food products. Shortening supply chains in some cases can reduce food loss by lessening the need for extended storage and distribution. Circular economy opportunities—such as the production of low-cost, high-quality animal feed; renewable energy usage; and improved food safety—can provide demonstrable benefits (panel 4).[509]

To address food waste in households and the food service and retail industries, education initiatives, awareness campaigns, and skill-building remain the primary solutions. Technical interventions focus on leveraging data and analytics to improve the efficiency of food supply chains. These interventions should be complemented by regulatory measures, taxes, and subsidies to increase their effectiveness.[510] A more systemic approach to reducing food waste should confront underlying drivers, institutional lock-ins (ie, situations where established practices and structures are resistant to beneficial change), and rebound effects.[511] For example, aesthetic standards and preferences of foods (eg, the size, colour, or presence of blemishes on fruits) imposed by markets contribute to supply chain losses and consumer waste. Similarly, current food safety laws and regulations, combined with existing investments in infrastructure, often favour incineration or landfill over alternative uses, such as feeding waste to animals.

Goal 3: secure social foundations

Solution 6: secure decent work

Several measures can be implemented to ensure that work within food systems is safe, dignified, and equitable without discrimination based on gender, race, or other forms of difference. Securing decent work requires, among other actions, raising wages for food systems workers to living wage levels[7] and promoting gender equality across all roles and sectors.[327] Food systems workers might be affected by the changes in production and consumption patterns that are essential for food systems transformation. For example, a reduction in livestock production could affect employment across local, regional, and national scales, depending on how and where such transitions occur.[512] Therefore, efforts to improve working conditions and prevent exploitation should include more robust implementation and enforcement of legislation against child labour and forced labour,[513] protection from exposure to agricultural pollutants,[514] and prevention of gender-based violence and sexual harassment in the workplace.[515] Governments should also prioritise educational initiatives and legal support mechanisms for workers to strengthen the enforcement and uptake of such protections.

Solution 7: ensure meaningful voice and representation

Securing meaningful voice and representation is essential for ensuring that decision-making processes in food systems are more democratic and inclusive. Collective bargaining mechanisms, supported and implemented through unions and civil society organisations, can advocate effectively for the rights and interests of food system workers and small-scale producers and actors. For policies concerning both production and consumption, the proactive engagement of diverse coalitions and perspectives—including unions, civil society actors, and marginalised populations—can foster more democratic and participatory decision-making governance.[324] Although these processes might be slowed by disagreements and trade-offs, expert facilitation and the establishment of clear procedural guidelines can help ensure momentum and constructive progress.[324] Importantly, such inclusive platforms can contribute to improved food systems governance by enabling interaction between actors across sectors and scales,[516] while also empowering local institutions and promoting decentralised decision-making authorities.[517]

Power imbalances also affect consumers, who often have little influence over the terms of food access, affordability, and quality.[496] Ensuring consumer representation through regulatory mechanisms, participatory food policy councils, and consumer advocacy groups can help rebalance these asymmetries and strengthen individual and collective agency within food systems governance.[518]

Additional measures to democratise food systems include the allocation of reserved seats in policy forums for marginalised groups,[519] the institutionalisation of citizens' assemblies, and consultations with citizenry and other food systems actors, both public and private.[520] Efforts to counter corporate influence and concentration should involve stricter regulations on donations to governments and other political parties, mechanisms to mitigate conflicts of interest, and greater transparency in the lobbying for and funding of scientific research.[20] Policies to address corporate concentration should include strengthened national and international competition frameworks,[20] alongside regulatory mechanisms to identify, monitor, and mitigate undue corporate influence on policy and governance processes.

Deliberate efforts to build inclusive coalitions that include marginalised groups, while also increasing transparency and accountability of food systems actors (both public and private), and expanding public access to information, can create new spaces for dialogue.

Solution 8: recognise and protect marginalised groups

Embedding justice into decision-making processes ensures that the responsibility for advocacy does not fall disproportionately on marginalised groups. The implementation of a comprehensive set of social protection policies can improve access to, and affordability of, healthy and sustainable diets. Social protection measures—including school meals (panel 10), unconditional cash transfers (ie, payments made to people with low income with no conditions), maternity entitlements, pensions, and disability benefits—are broad interventions that directly or indirectly improve food security and nutrition.[7,521]

Additional strategies to protect marginalised groups include financial support for women farmers, crop and livestock insurance to buffer against shocks, subsidies for farm inputs and technologies, and food price stabilisation mechanisms such as internationally coordinated food storage policies.[522] Ensuring that solutions are co-created with marginalised communities can help create context-specific and socially acceptable solutions.[523] Co-creation should be facilitated through improved representation (as previously discussed) and by engaging directly with affected groups, especially early in the food systems transformation process.[524] This co-creation also requires sustained support, including funding for inclusive initiatives and training programmes that build capacities for meaningful engagement within marginalised populations. Finally, non-governmental organisations have an important role in safeguarding basic human rights for people in conflict-affected areas, and this role should be supported by multilateral organisations and national governments. Interventions might include establishing safe zones as a short-term measure, rebuilding food supply chains with international assistance in the medium term, and creating dedicated funding mechanisms to prevent and alleviate famines in conflict areas over the long term.[391]

Adopt responsible, equitable technology and innovation across solutions

Although none of the aforementioned solutions explicitly focus on emerging technologies, technological innovation is relevant across food system transformation. Emerging technologies—such as artificial intelligence, cellular agriculture, nanotechnology, and robotics—have the potential to reshape and disrupt food and agricultural systems.[433,525] These innovations could enhance agricultural productivity without expanding land use, thereby contributing to reduced deforestation and habitat loss, and could also facilitate precision farming, reduce waste, and optimise the use of key inputs (eg, water and fertilisers).[433]

The effectiveness of these technologies will depend on balanced and strategic investments that align their development, deployment, and use with principles of equity, responsible innovation, and coherent policy frameworks,[526,527] along with the broader transition to renewable energy sources. Redirecting public and private funding towards emerging technologies that support the solutions described in this Commission will be essential. Comprehensive evaluation of new technologies to assess their impact on different geographical and cultural contexts is essential to ensure they contribute to a just food systems transformations.[528] This evaluation includes recognising that technologies can have both positive and negative effects, many of which remain uncertain—particularly in the case of rapidly advancing tools, such as artificial intelligence. To avoid or mitigate unintended environmental and social trade-offs, investments should be carefully targeted to ensure broad accessibility and fair distribution of the technologies.[525,527] Among the most discussed technologies relevant to dietary shifts are novel alternatives to replacing conventional meat; these alternatives, along with their potential implications for health, environment, and justice, are discussed in panel 11.

Panel 11: The potential role of meat alternatives in meeting EAT–Lancet targets

This Commission recommends a plant-rich diet with large shares of protein coming from minimally processed plant foods, such as legumes. We also find that globally, and in most regions, consumption of red meat and other meats is above healthy and sustainable levels. As consumer studies have revealed several barriers to replacing animal protein sources with traditional plant protein sources, including convenience, taste, and cultural values,[529] a range of meat alternatives are emerging across several regions, particularly in high-income countries. This range includes plant-based alternatives (PBAs), fermentation-derived products (that use microorganisms to produce protein-rich foods), and cultivated meat from animal cells designed to replicate the sensory properties of animal-sourced foods.[529] Previous systematic reviews[528,530] and modelling studies[28,530] suggest that replacing conventional meat with these alternatives could have positive and negative implications on health, the environment, and justice. These potential effects are context-dependent and vary based on the specific ingredients and processing levels of the alternatives, and what they replace within the diet.

Environmental implications

Whole foods that are high in plant protein, as well as traditional products prepared from these foods (eg, tofu and tempeh), have lower environmental impacts than animal foods. Meta-analyses and modelling studies indicate that PBAs can also have substantially lower environmental impacts compared with meat—particularly with regard to greenhouse gas (GHG) emissions and land use—but greater impacts than minimally processed plant foods.[528,530,531] Cultivated meat and fermentation-derived products are anticipated to have higher GHG emissions than PBAs and minimally processed plant foods, but lower or similar GHG emissions and land and water use levels compared with conventional meat products. The potential reduction is largely dependent on the food production system's transition to renewable energy sources.[532,533]

Health implications

Replacing red meat with legumes and other plant protein sources can provide several health benefits. The nutritional performance of emerging meat alternatives varies widely based on the product's formulation, level of processing, nutritional composition, and density, and on what they are replacing in the diet. PBAs that contain substantial amounts of legumes, vegetables, and nuts are found to have favourable nutritional profiles,[531] contributing to an increased intake of fibre and folate, and reduced saturated fat intake.[528,530] However, some PBAs are highly processed and are high in added sugar, salt, and saturated fat. Further research is required on the bioavailability of vitamins and minerals as well as the protein quality of PBAs and fermentation-based alternatives; such research would provide a better understanding of the nutritional effects of integrating them into diets. Cultivated meat is expected to have a similar nutritional profile as conventional meat and might therefore be similarly associated with colorectal cancer and other diet-related diseases.[530] The recommended consumption levels of processed meat alternatives are similar to those of conventional meat in table 1.

Justice implications

The implications of emerging meat alternatives on socioeconomic consequences (including food and nutrition security) is less understood than their environmental and health implications. Price is a key driver of purchase and consumption. Although unprocessed legumes are the least expensive form of plant protein, PBAs are often more expensive than the products they aim to replace.[530] Cultivated meats are not yet widely available, but the existing impartial peer-reviewed assessments suggest they will not be a cost-competitive product, even with substantial investment and improved production methods.[534–536] The alternative meat industry might also have implications for the labour market (eg, by generating and shifting employment from rural areas to cities).[497,532] As many large transnational food corporations enter the emerging market for meat alternatives, further market concentration or consolidation in the field of plant protein remains a concern.[497,537] Although emerging meat alternatives could mitigate animal welfare concerns, cultivated meat still involves some animal use through tissue biopsy removal.[538]

Section 6: a just food systems transformation is possible

The magnitude of changes needed to shift from an unsustainable status quo to the outcomes advocated for in this Commission are admittedly enormous. The differences between the present state, the projected trajectory under BAU scenarios for environmental and dietary patterns from the DIA-GIO model, and the projected trajectory needed for the desired future state (aligned with global adoption of the PHD, food system boundaries, and social foundations) are illustrated in figure 17. For all the variables where we have modelled current trends, we also show how substantially different the future trajectory needs to be compared with the current one.

To accelerate progress, the Commission calls for the development of transformative roadmaps to ensure that, by 2050, all individuals have access to healthy diets that are equitably produced, processed, and distributed within planetary boundaries. These roadmaps should be tailored to different sectors, scales, actors, and geographies. We propose five steps to guide their development: (1) establish context-specific bundles of actions and policies; (2) set and track targets that enable collective action and transparent accountability; (3) build coalitions of diverse actors; (4) identify and address barriers to change; and (5)

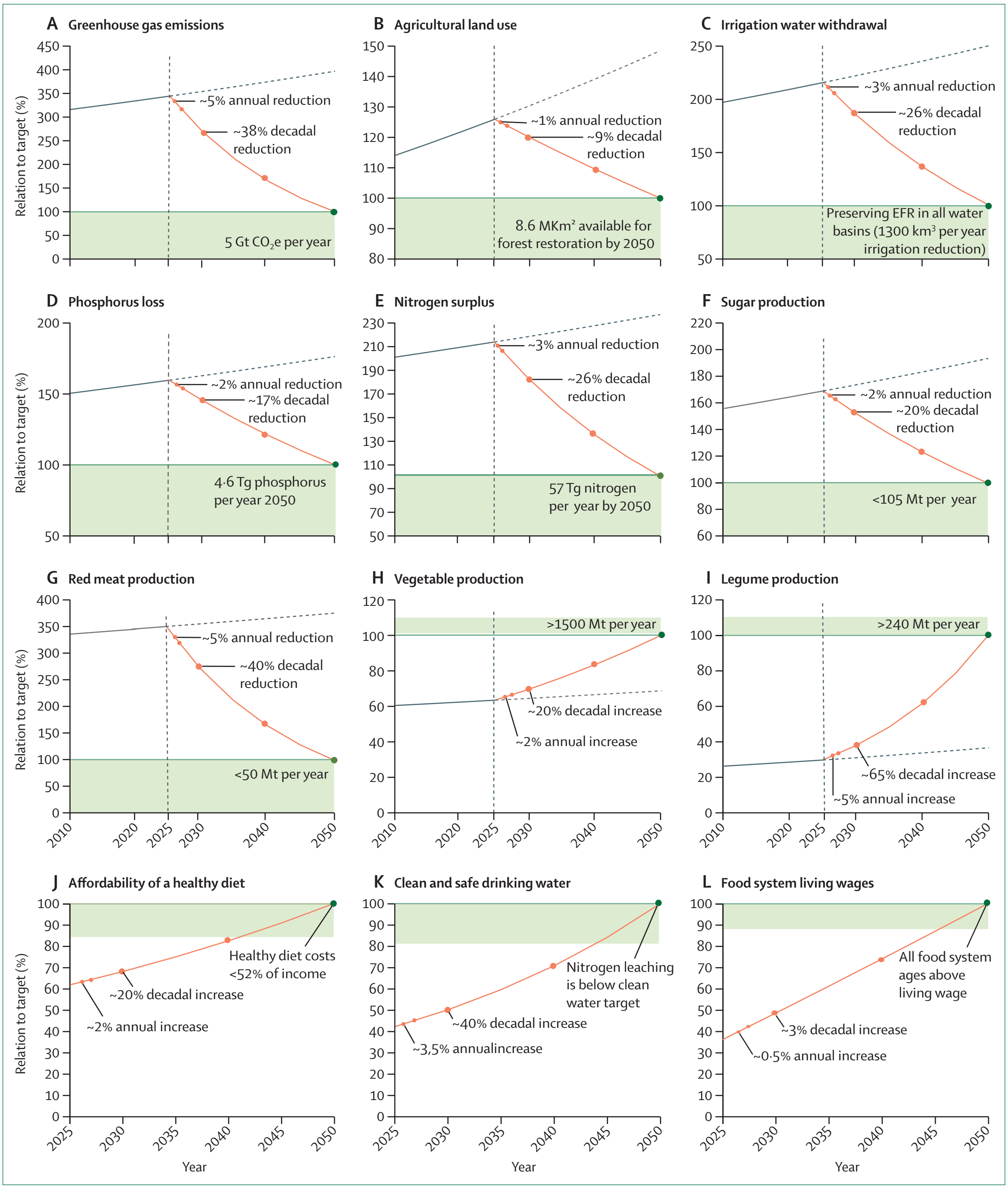


***Figure 17*: The development trajectories needed to meet the Commission's suggested targets for food production to support the planetary health diet, impacts on food system boundaries, and associated annual and decadal rate of change required to meet targets in 2050**

Environment targets (A–E) are based on the food system boundaries (table 2). Note that the requirement for irrigation water withdrawal is based on the aggregated regional overshoot of EFRs in water basins. Global production targets (F–I) are based on food demand following implementation of the planetary health diet and halving of FLW under the Shared Socioeconomic Pathways' middle-of-the-road scenario (SSP2), based on DIA-GIO model results. BAU scenario trajectories for production and environmental targets are also based on DIA-GIO model results. Social foundations (J–L) are based on ensuring everyone is above the social foundation (ie, 100% of the global population); trajectories show the current global population that is below each social foundation, based on recent estimates. Green spaces in all graphs represent the target zone. BAU=business as usual. CO_2e=CO_2 equivalent. DIA-GIO=Global Input–Output module of the Dietary Impact Assessment model. EFR=ecosystem flow requirements. FLW=food loss and waste.

unlock financial resources for transformation. These steps broadly align with previous work to develop implementation roadmaps for food systems,[205,433,539,540] climate, and biodiversity.[32] We elaborate on each step, highlighting its rationale and the enabling conditions for its success.

Establish context-specific bundles of actions and policies

All solutions identified in the previous section (figure 16) contribute to a specific goal (ie, health, sustainability, or justice), with potential positive or negative additional contributions to other goals. For example, fiscal policies aimed at promoting healthy diets (action 1) can yield co-benefits for both public health and environmental sustainability. However, such policies might also generate trade-offs with justice unless accompanied by public investments in social protection that increase purchasing power for low-income households (actions 3, 15, and 22–23). Although these interventions might independently contribute to shifts in production management and consumption patterns towards more sustainable and equitable outcomes, their transformative potential is only fully realised when implemented as contextually appropriate bundles of mutually reinforcing actions.

Bundling is the implementation of multiple actions simultaneously or in an intentionally staggered manner, and has been proposed as a necessary condition for food systems transformation.[32,541] We refer to bundles as "a coherent set of interventions designed explicitly to achieve a single or multiple objectives of interest".[12] An example of an action bundle is Nesta's blueprint to halve obesity in 5 years, a UK-based iniative that compares more than 30 intentionally integrated policies spanning different domains.

For more on **Nesta's blueprint** see https://blueprint.nesta.org.uk

Identifying and bundling actions is an inherently social process that requires cooperation and coordination beyond the implementation of a single policy or technical measure.[541] The bundling process extends beyond policy coherence by addressing both short-term and long-term objectives, which requires greater attention to how governance mechanisms can be adapted to manage such transitions (eg, balancing short-term needs and long-term objectives, which are often beyond the mandate of a single administration).[542] Resistance to change, often mobilised by actors adversely affected by specific measures, can constrain implementation.[541] Systematic bundling offers a way of mitigating trade-offs between political feasibility and policy effectiveness,[32,543] and can also increase the acceptability of measures by, for example, combining actions that increase costs for consumers (eg, taxes on meat) with those that offer discounts on low-emission food alternatives.[543] Integrating social protection mechanisms or retraining opportunities with prioritised interventions can help mitigate resistance by addressing short-term vulnerabilities associated with structural transitions.[541] For instance, combining actions to shift dietary patterns (solution 1) and implement SEI practices in healthy food production (solution 3) with the provision of training food systems workers in skills to support redeployment (action 16) can support the broader goal of securing decent work (solution 6).

Well sequenced and gradually enacted policies can generate positive tipping points,[544] whereby early successful interventions build public trust and facilitate broader acceptance of subsequent reforms. In contexts where interventions are met with scepticism or bias, combining interventions with robust evaluations can foster support over time, allowing citizens to engage with the interventions directly and observe its effects.[545] Careful policy sequencing is therefore essential: poorly timed or misaligned reforms can erode confidence in government abilities, undermining legitimacy for future initiatives. For example, changes in agricultural management require time to build the necessary skills and conditions to adopt SEI practices. In Sri Lanka, the abrupt ban on agrochemicals in pursuit of organic agriculture failed to account for the time required to train farmers in organic techniques, build soil organic matter, and develop integrated pest management practices.[546] This poor planning led to collapsing yields, which could have been avoided with a more phased and strategically sequenced policy roll out. Similar challenges have arisen in the Netherlands, with the implementation of nitrogen regulations,[547] and in France, where the fuel tax contributed to the emergence of the Yellow Vest movement.[548]

Governments can enhance their ability to effectively bundle, sequence, and prioritise interventions through institutional mechanisms that foster cross-sectoral collaboration—such as coordination between ministries—and by partnering more closely with research organisations. An example of this type of partnership is Brazil's Fome Zero (Zero Hunger) programme,[549] which integrated efforts across its ministries of health, education, and social development, in collaboration with research organisations. The programme strategically bundled policies including cash transfers for households with low income, support for small-scale farmers, and nutrition education to address food insecurity and promote sustainable agriculture.[549]

Prioritising different actions in different regions

Bundles of actions for food systems transformation will vary substantially across contexts. For example, consumer-based actions to achieve adoption of the PHD (solution 1) should be a high priority in HICs and UMICs, as these countries' consumption rates per capita disproportionately contribute to planetary boundary transgression. The per capita external costs to human health and ecosystems are nearly four times higher in North America and Oceania than in sub-Saharan Africa,[550] despite the relative burden of these costs (as a share of GDP) being greater in LICs than in HICs. HICs[11] also bear a large responsibility for reducing energy-related emissions and supporting food systems improvements in LMICs[551]—efforts that are essential to achieving the ELM pathway modelled in this Commission. The societal benefits of dietary shifts towards the PHD would be especially high in HICs and UMICs.[11]

In many LICs and MICs, priorities should instead include maintaining existing healthy dietary patterns (especially in their youth populations), addressing hunger and undernutrition, and preventing expansion of unhealthy diets (solution 2). MICs, in particular, have the greatest overall potential to reduce food systems-related climate emissions on the production side by shifting towards more sustainable agricultural practices (eg, solution 3) and adopting cleaner, more circular processing systems (solution 5).[551]

Other work,[552] which includes stakeholder consultations on priorities for regional food systems, have highlighted the several focal areas for prioritisation: increasing food availability in east and southern Africa; promoting income growth in west and central Africa; improving the nutritional quality of diets in the Pacific; and protecting against deforestation in Latin America.

Set and track targets to enable collective action and accountability

Target setting has emerged as a strategy to align diverse actors around shared ambitions and responsibilities, improve policy integration, and help overcome barriers to transformation.[542] Global targets can shape international agendas and catalyse bold policies across multiple scales. For example, net-zero emissions targets aligned with the Paris Agreement—although insufficient on their own—have nonetheless accelerated progress in carbon markets (eg, through the EU Emissions Trading System) and spurred rapid expansion of renewable energy development.

The identification of PHD reference values and ranges, food system boundaries, and social foundations represents an initial step towards establishing science-based targets for food systems. Although global targets can foster a shared vision and ambition, their translation into tangible actions across scales and sectors is essential for achieving meaningful impact.[553] Such target setting should be grounded in independent scientific assessments, be attainable and actionable, and be supported by a transparent analytical rationale. Achievement of these targets should be measurable.[554] Science-based targets are most effective when developed and implemented through inclusive dialogues with diverse stakeholders.[555] Methodological advancements to enable disaggregation of targets (and their indicators) across geographical scales (ie, local, municipal, national, or global) and across sectors are greatly needed.[554]

Voluntary, science-based target commitments are increasingly being adopted by companies, cities (eg, panel 12), and national governments—such as as the wide uptake of the Voluntary Guidelines on Food Systems and Nutrition, established by the Committee on World Food Security.[556] These voluntary commitments have corresponded with increased action,[557] especially in the climate domain. Corporate initiatives can drive transformation by leveraging their leadership positions, enabling mutual learning for adopters of science-based targets, and fostering trust and competitiveness through engagement with expert groups and accountability mechanisms.[558]

However, research on voluntary, science-based target setting remains nascent. Emerging evidence suggests that without effective implementation, monitoring, and evaluation of these targets, such commitments could risk hindering transformative change—for example, by legitimising powerful corporate actors and insulating them from democratic oversight.[557] To accelerate progress and ensure measurable improvements, transitioning science-based targets from voluntary frameworks to regulatory mechanisms is essential.[556]

Ensure monitoring and evaluation of targets and actions

Improved monitoring across food systems is essential for monitoring progress towards proposed targets, and for informing adaptive, evidence-based decision making. Recent calls from the scientific community have emphasised the need for monitoring frameworks that move beyond tracking isolated indicators and instead focus on integrated, multilayered, cross-sectoral data—connecting analyses that have traditionally been treated in silos.[559,560] Such approaches enhance compliance and accountability.[559]

One example of such monitoring frameworks is the Food Systems Countdown to 2030 Initiative,[34,540] which promotes greater accountability and transparency across and between countries and their citizenry through comprehensive global monitoring of food systems across five domains: diets, nutrition, and health; environment, natural resources, and production; livelihoods, poverty, and equity; governance; and resilience.[34,561] Robust monitoring and evaluation systems are also important for supporting learnings about what works, particularly given the scarce context-specific evidence on the effectiveness of food systems interventions, particularly when bundled.[32] Monitoring and evaluation frameworks should therefore facilitate the iterative refinement of strategies and actions in response to emerging evidence and shifting conditions.[562]

The current evidence gaps, combined with the urgent need for action, underscore the need to improve science–policy interfaces through greater integration, iteration, and interaction among researchers, policy actors, and stakeholders in society.[563,564] Effective monitoring and evaluation frameworks should be co-developed by multiple stakeholders, including governments, industries, civil societies, and research institutions.[433,527] Although scientific assessments have a key role in synthesising

Panel 12: The C40 Initiative to achieve the planetary health diet for all by 2030

Launched in October, 2019, by C40 (a global network of almost 100 mayors of leading cities committed to addressing climate change), 16 cities signed up to an ambitious initiative aiming to achieve the planetary health diet (PHD) for all by 2030 in ways that are reflective of the culture, geography, and demography of their residents. Seven of the cities are in Europe, five in North America, one in South America, two in east Asia, and one in southeast Asia.

The participating cities pledge to implement four important measures by 2030:

- Align their food procurement to the PHD.
- Support an overall increase of healthy, plant-based food consumption by shifting away from unsustainable, unhealthy diets.
- Reduce food loss and waste by 50% from a 2015 baseline.
- Work with residents, businesses, public institutions, and other organisations to develop a joint strategy to implement these measures and achieve these goals inclusively and equitably, and incorporate this strategy into climate action plans, including incorporation into Nationally Determined Contributions to climate goals.

Interim evaluation

In September, 2023, 15 of the 16 participating cities submitted interim reports on their progress. Sufficient data were provided by seven cities to quantify progress towards the first two measures. Between them, these seven cities serve over 400 million meals a year for different groups and establishments, including schools and hospitals. When measured against different baseline years between 2015 and 2022, cities reported a 44% increase in their purchasing of plant-sourced protein (from a mean of 6356 to 8667 tonnes) and a 19% reduction in their meat purchasing (from a mean of 16 648 to 12 765 tonnes). In recognition of its significant potential in making millions of meals in major cities healthier and more sustainable, in June, 2024, this initiative won the prestigious $2 million Food Planet Prize awarded by the Curt Bergfors Foundation.

Many examples of progress towards all four measures were described by cities in the interim evaluation in 2023, including engaging with citizens, restaurants, store owners, and town planners to change food environments and make healthier and sustainable options more readily available, and offering training for businesses on how to reduce food waste.

Although excellent examples abound, the extent of progress for each of the four measures across all 16 cities remains unknown at the time of writing because monitoring systems with similar robust metrics across all cities have yet to be put in place.

Barriers to progress reported by cities

Two barriers to progress were commonly reported by participating cities:

- National procurement standards are misaligned and do not consider the environmental impact of foods purchased. To achieve the PHD for all, cities are having to justify and then implement their changes throughout the entire public food supply chain on their own.
- Budgetary restrictions, coupled with increasing food prices, are curtailing cities' capacity to gather data on their progress towards each of the four aims of this initiative, leading to insufficient resources for evaluation.

Maximising the impact of the C40 Good Food Cities Initiative

Providing additional resources to the C40 Good Food Cities initiative is crucial for maximising its impact and value as a global exemplar of transitioning food systems, by achieving the following:

- Establishing monitoring mechanisms to assess progress and adjust processes that are misaligned with achieving its 2030 goal.
- Creating multilevel platforms to engage different authorities and citizens in creating a shared vision.
- Supporting campaigns and other forms of advocacy to inspire national governments and international partners to increase their ambition and action at the scale needed to achieve the PHD for all.

Lessons from all C40 initiatives in making the planetary health diet accessible for all

Mayors from 16 cities around the world are leading the way in transforming the food in their cities. Similar ambitious initiatives are now needed in every city, town, and village on our planet to achieve the PHD for all. However, the efforts of these pioneering cities highlight that realising these ambitions will require each initiative to be matched—at its inception—by sufficient resources for two core activities:

- Implementing a programme of interventions built on existing evidence.
- Robust evaluation included from inception as part of the implementation plan, so that progress is monitored in real time. This evaluation will allow promising interventions to be optimised, ineffective interventions to be stopped, and potential interventions to be started.

existing knowledge, novel tools are required to evaluate the effects of bundled and sequenced interventions, rather than isolated actions.[565]

Stronger alignment between global and sub-global assessments—such as those from the *Lancet* Commissions, the Food System Economic Commission, the High-Level Panel of Experts on Food Security and Nutrition, and the International Panel of Experts on Sustainable Food Systems—and corresponding assessments on climate, environment, biodiversity health, and justice (eg, by the IPCC, IPBES, and the Earth Commission) would enhance the capacity of governments and policy makers to integrate and leverage collective knowledge across domains.[560] National food systems pathways, supported by the UN Food Systems Summit, offer a timely opportunity to develop integrated roadmaps that connect food systems transformation with climate, biodiversity, health, and economic objectives.

Build coalitions of diverse actors

Effective bundling of actions requires coalitions of actors to negotiate between competing interests, navigate difficult choices,[433,541] and ensure that the necessary capacities (eg, learning, engagement and collaboration, capabilities, legal frameworks, and infrastructure) are deployed for transformation.[566] The 2021 UN Food Systems Summit, and its 2023 and 2025 Stocktaking Moments, highlighted coalitions as essential for addressing food systems' multisectoral and multiscalar challenges, leading to more than 20 coalitions being formed to deal with issues such as the provision of school meals (panel 10), deforestation, agroecology, aquatic foods, data transparency, and fair wages.[567]

Coalitions can allow various actors with diverging interests and perspectives to negotiate more inclusive, viable, and realistic food systems pathways.[563] Policies within food systems will affect communities in different ways, and tensions between stakeholders will need to be managed.[12] For instance, a fear of job losses in certain sectors can slow or stall reforms towards sustainability. In such cases, coalitions could negotiate ways to compensate those affected or invest in new opportunities that would benefit them.[12]

Different food system actors have varying capacities to enact change. Interventions that could enable system shifts have sometimes stalled, often due to delays and bottlenecks in regulatory processes.[7] Communities, international non-governmental organisations, and other stakeholders can deploy different capabilities to support transformation in different ways. By forming stronger alliances and coalitions, these actors can implement more coordinated and timely interventions for transformative change.[568] Realising food systems transformation will require novel forms of partnership among intergovernmental and global institutions, national governments, and sub-national public authorities (eg, cities, states, and municipalities). Cross-ministry committees can align policies across sectors. Engagement from the private sector, civil society, and citizen-led movements is equally important.[551] Different actors bring distinct capacities and mandates that have unique roles in shaping systemic change.[528] Transformation cannot occur without forging coalitions that span boundaries, reconcile different interests, and build legitimacy for new policy pathways.[566,569] Initiatives such as the UN Zero Hunger Coalition, the EU Farm to Fork Strategy, and the School Meals Coalition (panel 10) illustrate how diverse competencies and agendas can be integrated to advance health, environmental sustainability, and justice in tandem.

Identify and address barriers to change

Coalitions aiming to advance food systems transformation involve actors and stakeholders with different interests and tactics to preserve such interests, which are sometimes designed to maintain the status quo.[570,571] These competing interests shape the incentives and constraints surrounding transformative efforts.[541] For coalitions to function effectively, three key barriers should be addressed: (1) insufficient political leadership; (2) corporate interests; and (3) weak and fragmented demand for action.

Insufficient political leadership and appropriate governance framework

Political leadership has been notably absent in driving transformative food policy agendas and committing resources to long-term structural change to food systems.[496] Short electoral cycles often discourage support for policies whose benefits, such as improvements in population health, are realised beyond a single political term. This hesitancy is compounded by substantial upfront investments required for transformation, and the perceived risks these pose to factors such as employment and food prices.[12,572] Moreover, government subsidies often favour large corporate actors over broader policies to promote public welfare and public goods.[573]

Effective transformation requires coordinated, intersectoral policy actions that extend beyond food systems themselves. However, current governance arrangements often fail to systematically address and integrate agriculture and the environment, health and nutrition, infrastructure, energy, growth, and equity into these policies.[561]

Corporate interests used against public interests

The second major barrier to functional coalitions is the exercise of corporate power in ways that undermine public interests. The high degree of corporate concentration across food systems remains an intractable governance issue,[397,574] which is partly due to the vast influence of large transnational food and beverage companies with considerable power and resources at their disposal to block initiatives.[23] Concentrated market structures, with a few dominant firms, are common in all aspects of the food system, from production (ie, agricultural inputs) and trade (ie, commodity trade), to consumption (ie, food processing and retail).[20,575] This concentration affects people's access to food through strategies including manipulative pricing, and advertising and packaging that shapes consumers' preferences.[576] Corporate actors use tactics such as directly lobbying governmental officials to undermine political priorities, including dietary guidelines and regulatory interventions.[577] Another avenue of influence by corporations is in the sponsorship of scientific studies that align with their commercial interests, and the dissemination of misinformation aimed at discrediting independent scientific evidence—such as in cases involving scientists sponsored by the meat industry.[578,579] Furthermore, public–private partnerships are increasingly co-opted by corporate actors to shape discourse, particularly in the area of sustainability, in ways that reinforce their legitimacy and market power.[580,581]

Weak and fragmented demand for action

A perceived lack of effective public demand and acceptance for transformative change is frequently cited by policy makers and private sector actors as justification for deprioritising ambitious reforms. Citizens might resist policies that ultimately serve the public due to the difficulty of weighing short-term costs, particularly in terms of employment in affected sectors, against long-term benefits.[545,562]

Although citizen-led movements have an important role in building public engagement and political momentum for more equitable and sustainable food systems,[582] their efforts are often fragmented and constrained by entrenched power dynamics and the structural inequities of food systems.[575,583] In some repressive political contexts, civil society and citizen-led organisations are deliberately excluded or marginalised by authoritarian regimes, further silencing calls for change. In other contexts, citizen-led mobilisation can cause polarisation over policies that might not promote public good over the long term.

Fragmentation in public demand can also stem from a lack of consensus on priorities and insufficient space for dialogue—particularly for facilitated, inclusive processes that can clarify areas of disagreement and forge common ground.[555] These challenges are especially pronounced with global commitment mechanisms—such as the Paris Agreement or the Kunming–Montreal Global Biodiversity Framework—being translated into local or national actions.[26] Misinformation further compounds public disengagement, especially when systemic challenges (eg, public health) are framed as matters of individual responsibility. This framing distorts public understanding of the structural determinants of necessary reforms and diminishes support.[584] The absence of transparent monitoring systems exacerbates this problem by undermining public trust in transformational policies and fostering uncertainty or misconceptions about their potential for delivering broad-based benefits.[585]

Unlocking financial resources for transformation

Estimates have shown that substantial financial resources—$500 billion per year between 2025 and 2050—are needed to enable necessary food systems transformations.[12] However, the benefits of these transformations could amount to more than 5 trillion a year,[12] and not all actions require large amounts of financial resources to be successful. Some can be implemented at moderately low cost or can even be cost-neutral. However, these actions require willingness from governments to reprioritise current resource spending. Here, we look at the potential to unlock resources within the food system, primarily through bundling of different activities that already occur. We then explore how bundling these activities with broader policy agendas can optimise additional resources.

Repurposing subsidies, and other food systems investments

Subsidies to the agricultural sector represent a substantial resource, estimated at roughly $851 billion in the 2020–22 period (for the 54 countries that report to the Organization for Economic Cooperation and Development). The Food Systems Economic Commission has estimated that the cost of food systems transformation is between $200 billion and $500 billion per year.[12] Without changing the degree of financing currently provided to the food production sector, setting clear conditions for the use of these earmarked public funds in favour of public goods, such as public health and environmental security, would be a major first step towards transformation.[490] At least a third of agricultural subsidies have no public benefit and could be repurposed.[586] In the EU, 82% of agricultural subsidies favour animal-based agriculture.[586] Farm sector subsidies could be used to incentivise or invest in SEI practices, focusing on the management of opportunity crops that are currently neglected while also promoting dietary change.[500] Fisheries subsidies of around $35 billion per year could support sustainable aquatic production practices rather than contribute to falling fish stocks and declining profitability, which in turn fuels more overfishing and environmentally damaging forms of land-based aquaculture.[587]

Shifts in agricultural and other subsidies (eg, health, transportation, or infrastructure) or value-added tax can reduce costs to the health-care sector, increase health benefits, and lower climate impacts.[446] Health-directed taxation of meat products could yield a 9% decrease in premature deaths associated with red and processed meat consumption, with an estimated 14% decrease in attributable health costs globally, especially in HICs and MICs.[446]

Measures that seek to distribute income more equitably (eg, via social protection measures or progressive tax policies), combined with a serious public and private sector commitment to reducing FLW in all food value chains, can improve the relative affordability of healthy dietary patterns. When these measures were combined with others in a previous modelling effort, the cost of diets aligned with the PHD fell by 25–29% in LICs and LMICs.[11] However, the substantial restructuring of any sector—including the repurposing of any subsidy—should be handled with care, as the potential unintended effects of shifting resources from one targeted purpose to another can be as substantial as the intended effects.[588]

Aligning investments with climate, nature, and economic agendas

Another way to unlock resources for food systems transformation is to align approaches and financial priorities with other mutually interdependent policy and investment agendas. A share of climate or biodiversity finance funding could be repurposed for food systems transformation. For example, at the Conference of Parties (COP) climate summit in Egypt in 2022, the COP Presidency and WHO launched the Initiative on Climate Action and Nutrition, to better integrate the global delivery of climate change adaptation and mitigation goals and the policy action necessary to meet nutrition and sustainable food systems goals.[589] This alignment requires future summit agendas, focused on aspects such as climate, fossil fuels, renewable energy, employment growth, and food systems, to work towards the integration of targets and investment modalities. However, many iniatives are currently not aligned with agricultural policies, or with other policies at different levels. For example, initiatives for tree planting remain largely uncoordinated, despite showing considerable benefits for food security, nutrition, and the environment.[590,591] By intensifying these alignment efforts, governments can work more strategically to integrate and coordinate these multiple agendas to repurpose fiscal incentives away from so-called economic bads (eg, carbon emissions, biodiversity destruction, and consumption of excessive sugar, salt, or trans fats) towards public goods.[592]

In 2022, subsidies to the energy sector (which are currently driven by fossil fuels) were estimated to be around $7 trillion.[593] Ending subsidy support for polluting energy production practices would allow for a repurposing of resources to alternative public sector investments.[594] These investments could be in regenerative energy practices to support diet quality through solar-powered drying and chilling of perishable foods, and other innovations in cold chain technologies that reduce nutrient-rich FLW. However, project-level climate financing for food systems stands at only 4·3%, or $28 billion, of global climate finance for mitigation and adaptation in all sectors, with specific mitigation finance in the food sector being only 2·2% of total climate finance.[551] In their Recipes for a Liveable Planet report, the World Bank estimates that annual investments in reducing food systems emissions will need to increase by 18 times, to $260 billion, to halve current food systems emissions by 2030.[551]

Different methods of unlocking finance for food systems transformation could be successful if banks, investors, and large businesses adopt and report against the Task Force on Climate-Related Financial Disclosures, help develop the Taskforce on Nature-related Financial Disclosure, and set targets in line with the Science Based Targets Initiative and the Paris agreement.[595] Through these agendas, financial institutions can make various commitments to shift towards more sustainable food systems, such as deforestation-free portfolios (eg, deforestation-free pension funds). Public spending should also create mechanisms for private investment in food systems transformation. For example, central banks can introduce stress testing for financial institutions based on their viability in a future economy that fully accounts for negative externalities.

The cost of food systems transformation for low-income regions are beyond their current financing capacity. Eliminating their financing constraints is essential for unlocking the global benefits of transformation.[551] Countries with insufficient fiscal capacity need international support to invest in food systems sustainability.[593]

Wealthy countries and other donors should increase both their Official Development Assistance from the current low levels (relative to their actual and projected national wealth), and their climate finance for food systems adaptation through multilateral development finance institutions. Furthermore, wealthy governments can introduce targeted debt relief to facilitate the flow of capital to food systems transformations, including debt for food swaps. This action could be supported by innovative financial instruments, such as guarantees for a new type of perpetual or long-term social and environmental bond, with capped adjustable rates.

Conclusions: accelerating meaningful action

This Commission calls for an urgent, comprehensive approach to food systems transformation, centred on the development of context-specific roadmaps that provide viable, evidence-based solution sets. Such roadmaps should focus on bundling actions, setting science-based targets, building inclusive coalitions, establishing and building on already existing monitoring and accountability mechanisms, and mobilising financial resources at scale. At the core of our Commission's framework are three foundational elements: (1) recommended food group intake values for the PHD to advance human health; (2) food system boundaries to achieve environmental sustainability; and (3) social foundations to guide the creation of just food systems. These values, boundaries, and foundations can guide target setting and collective action, and are adaptable across geographies and sectors.

This Commission has identified eight solutions and 23 actions to enable food systems transformation, which can be organised into coherent bundles of interventions that simultaneously advance health, environmental, and justice goals. Bundling enhances political feasibility and policy effectiveness, particularly when designed to prioritise the needs of marginalised and disadvantaged populations. The most suitable and effective bundles will vary by context and should be tailored to the specific challenges and opportunities of each region and sector.

Cross-sectoral coalitions—including actors from public institutions, private sector, and civil society—are essential to achieve synergistic governance. These coalitions should align with existing and emerging global frameworks, such as the Paris Agreement, the Convention on Biological Diversity, and the post-2030 Sustainable Development Goals agenda. Ensuring accountability within these coalitions is essential. Mechanisms should be established to insulate policy making from undue corporate influence, and civil society and social movements should be recognised for their important roles in promoting transparency and oversight.

This Commission also underscores the need for actions beyond the food system. Its modelling indicates that the PHD can only be achieved within GHG and land-use planetary boundaries if mitigation efforts in other sectors are also scaled up. Similarly, shifting diets within low-income and vulnerable groups requires coupling dietary interventions with broader social protection measures. Affordability should be achieved not only by reducing food prices, but by addressing structural poverty and inequities. Financing for food systems transformation should draw from broader funding streams—such as those targeting climate mitigation and biodiversity conservation and protection—rather than relying solely on current food systems financing.

Finally, our Commission positions justice as both a central goal and a driving force for food systems transformation. Food systems cannot be just without ensuring the PHD is affordable and accessible to all, and without substantially reducing transgressions of planetary boundaries. Justice is also necessary to overcome the deeply entrenched structural barriers that currently impede transformative change. In this sense, justice is not only an outcome of food systems transformation, but a prerequisite for enabling it.

Contributors

This Commission is co-chaired by JR, SHT, and WCW, together with the leadership team (ie, FDeC, LJG, MH, CCH, and ECW). The co-chairs and the leadership team developed the idea, conceptualisation, and structure of the Commission, including integration across sections.

The Commissioners and postdoctoral research fellows conducted thematic assessments of each section of the Commission, and of the work as a whole (ie, RAg, SB, ACB, BC, CCo, NC, JF, NGF, MFG, XG, EK, CK, AL, RL, TMM, DM-D'C, CAM, AN, JN, TDO, W-HP, NR, JAR, JPWR, MSp, MSu, StW, DPvV, SV, and PW). Additional authors were included to make detailed contributions on areas of specific disciplinary expertise (ie, LA, RAm, AB, IB, FB, DB, AHWB, JB, CCh, MC, JC, WdV, NE-C, IP-D, DG, CDG, SKJ, PSJ, MK, HL-C, FM, EM, AM, FO-C, AP, LS-U, ES, FHMT, KT, HHEVZ, W-JvZ, and XZ). All Commissioners and postdoctoral research fellows conducted reviews and writing for specific sections (ie, those on healthy diets, food system planetary boundaries, sustainable and ecological intensification, just food systems, modelling, food system solutions, and food systems transformation). Each Commissioner and postdoctoral research fellow contributed to at least one section, but often to more than one. The model intercomparison included in this study was led by DM-D'C and MH, with support from MSp, MHG, TDO, and MSu.

The intercomparison included ten dynamic global food system models (ie, AIM, CAPRI, ENVISAGE, FARM, GCAM, GLOBIOM, IMPACT, IMAGE, MAGNET, and MAgPIE) and the static DIA-GIO model, with two additional models for specific deep-dives (ie, FABLE and CiFoS).

Declaration of interests

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