# Food in the Anthropocene: the EAT–*Lancet* Commission on healthy diets from sustainable food systems

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## Executive summary

Food systems have the potential to nurture human health and support environmental sustainability; however, they are currently threatening both. Providing a growing global population with healthy diets from sustainable food systems is an immediate challenge. Although global food production of calories has kept pace with population growth, more than 820 million people have insufficient food and many more consume low-quality diets that cause micronutrient deficiencies and contribute to a substantial rise in the incidence of diet-related obesity and diet-related non-communicable diseases, including coronary heart disease, stroke, and diabetes. Unhealthy diets pose a greater risk to morbidity and mortality than does unsafe sex, and alcohol, drug, and tobacco use combined. Because much of the world's population is inadequately nourished and many environmental systems and processes are pushed beyond safe boundaries by food production, a global transformation of the food system is urgently needed.

The absence of scientific targets for achieving healthy diets from sustainable food systems has been hindering large-scale and coordinated efforts to transform the global food system. This Commission brings together 19 Commissioners and 18 coauthors from 16 countries in various fields of human health, agriculture, political sciences, and environmental sustainability to develop global scientific targets based on the best evidence available for healthy diets and sustainable food production. These global targets define a safe operating space for food systems that allow us to assess which diets and food production practices will help ensure that the UN Sustainable Development Goals (SDGs) and Paris Agreement are achieved.

We quantitatively describe a universal healthy reference diet to provide a basis for estimating the health and environmental effects of adopting an alternative diet to standard current diets, many of which are high in unhealthy foods. Scientific targets for a healthy reference diet are based on extensive literature on foods, dietary patterns, and health outcomes. This healthy reference diet largely consists of vegetables, fruits, whole grains, legumes, nuts, and unsaturated oils, includes a low to moderate amount of seafood and poultry, and includes no or a low quantity of red meat, processed meat, added sugar, refined grains, and starchy vegetables. The global average intake of healthy foods is substantially lower than the reference diet intake, whereas overconsumption of unhealthy foods is increasing. Using several approaches, we found with a high level of certainty that global adoption of the reference dietary pattern would provide major health benefits, including a large reduction in total mortality.

The Commission integrates, with quantification of universal healthy diets, global scientific targets for sustainable food systems, and aims to provide scientific boundaries to reduce environmental degradation caused by food production at all scales. Scientific targets for the safe operating space of food systems were established for six key Earth system processes. Strong evidence indicates that food production is among the largest drivers of global environmental change by contributing to climate change, biodiversity loss, freshwater use, interference with the global nitrogen and phosphorus cycles, and land-system change (and chemical pollution, which is not assessed in this Commission). Food production depends on continued functioning of biophysical systems and processes to regulate and maintain a stable Earth system; therefore, these systems and processes provide a set of globally systemic indicators of sustainable food production. The Commission concludes that quantitative scientific targets constitute universal and scalable planetary boundaries for the food system. However, the uncertainty range for these food boundaries remains high because of the inherent complexity in Earth system dynamics.

Diets inextricably link human health and environmental sustainability. The scientific targets for healthy diets and sustainable food systems are integrated into a common framework, the safe operating space for food systems, so that win-win diets (ie, healthy and environmentally sustainable) can be identified. We propose that this framework is universal for all food cultures and production systems in the world, with a high potential of local adaptation and scalability.

Application of this framework to future projections of world development indicates that food systems can provide healthy diets (ie, reference diet) for an estimated global population of about 10 billion people by 2050 and remain within a safe operating space. However, even small increases in consumption of red meat or dairy foods would make this goal difficult or impossible to achieve. Within boundaries of food production, the reference diet can be adapted to make meals that are consistent with food cultures and cuisines of all regions of the world.

Because food systems are a major driver of poor health and environmental degradation, global efforts are urgently needed to collectively transform diets and food production. An integrative framework combined with scientific targets

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## Key messages

1. Unhealthy and unsustainably produced food poses a global risk to people and the planet. More than 820 million people have insufficient food and many more consume an unhealthy diet that contributes to premature death and morbidity. Moreover, global food production is the largest pressure caused by humans on Earth, threatening local ecosystems and the stability of the Earth system.
2. Current dietary trends, combined with projected population growth to about 10 billion by 2050, will exacerbate risks to people and planet. The global burden of non-communicable diseases is predicted to worsen and the effects of food production on greenhouse-gas emissions, nitrogen and phosphorus pollution, biodiversity loss, and water and land use will reduce the stability of the Earth system.
3. Transformation to healthy diets from sustainable food systems is necessary to achieve the UN Sustainable Development Goals and the Paris Agreement, and scientific targets for healthy diets and sustainable food production are needed to guide a Great Food Transformation.
4. Healthy diets have an appropriate caloric intake and consist of a diversity of plant-based foods, low amounts of animal source foods, unsaturated rather than saturated fats, and small amounts of refined grains, highly processed foods, and added sugars.
5. Transformation to healthy diets by 2050 will require substantial dietary shifts, including a greater than 50% reduction in global consumption of unhealthy foods, such as red meat and sugar, and a greater than 100% increase in consumption of healthy foods, such as nuts, fruits, vegetables, and legumes. However, the changes needed differ greatly by region.
6. Dietary changes from current diets to healthy diets are likely to substantially benefit human health, averting about 10·8–11·6 million deaths per year, a reduction of 19·0–23·6%.
7. With food production causing major global environmental risks, sustainable food production needs to operate within the safe operating space for food systems at all scales on Earth. Therefore, sustainable food production for about 10 billion people should use no additional land, safeguard existing biodiversity, reduce consumptive water use and manage water responsibly, substantially reduce nitrogen and phosphorus pollution, produce zero carbon dioxide emissions, and cause no further increase in methane and nitrous oxide emissions.
8. Transformation to sustainable food production by 2050 will require at least a 75% reduction of yield gaps, global redistribution of nitrogen and phosphorus fertiliser use, recycling of phosphorus, radical improvements in efficiency of fertiliser and water use, rapid implementation of agricultural mitigation options to reduce greenhouse-gas emissions, adoption of land management practices that shift agriculture from a carbon source to sink, and a fundamental shift in production priorities.
9. The scientific targets for healthy diets from sustainable food systems are intertwined with all UN Sustainable Development Goals. For example, achieving these targets will depend on providing high-quality primary health care that integrates family planning and education on healthy diets. These targets and the Sustainable Development Goals on freshwater, climate, land, oceans, and biodiversity will be achieved through strong commitment to global partnerships and actions.
10. Achieving healthy diets from sustainable food systems for everyone will require substantial shifts towards healthy dietary patterns, large reductions in food losses and waste, and major improvements in food production practices. This universal goal for all humans is within reach but will require adoption of scientific targets by all sectors to stimulate a range of actions from individuals and organisations working in all sectors and at all scales.

can provide essential support for a sustainable and healthy food transformation. This Commission concludes that global food systems can provide win-win diets to everyone by 2050 and beyond. However, achieving this goal will require rapid adoption of numerous changes and unprecedented global collaboration and commitment: nothing less than a Great Food Transformation.

We focus mainly on environmental sustainability of food production and health consequences of final consumption. However, the food system consists of much more than these factors. A transformation of the global food system should ultimately involve multiple stakeholders, from individual consumers to policy makers and all actors in the food supply chain, working together towards the shared global goal of healthy and sustainable diets for all.

However, humanity has never aimed to change the global food system on the scale envisioned in this Commission; this objective is uncharted policy territory and the problems outlined in this Commission are not easily fixed. Three lessons can be learned from other examples of societal responses to global changes. First, no single actor or breakthrough is likely to catalyse systems change. Second, science and evidence-gathering are essential for change. Third, a full range of policy levers, from soft to hard, will be needed. Together, these lessons guide the thinking that will be necessary to transform the global food system. In addition, we outline five specific and implementable strategies, which are supported by a strong evidence base. Our modelling and analysis shows their effectiveness for achieving a Great Food Transformation. These strategies are:

(1) Seek international and national commitment to shift towards healthy diets. The scientific targets set by this Commission provide guidance for the necessary shift, which consists of increasing consumption of plant-based foods and substantially reducing consumption of

animal source foods. Research has shown that this shift will reduce environmental effects and improve health outcomes. This concerted commitment can be achieved by investment in public health information and sustainability education, and improved coordination between departments of health and environment.

(2) Re-orient agricultural priorities from producing high quantities of food to producing healthy food. Production should focus on a diverse range of nutritious foods from biodiversity-enhancing food production systems rather than increased volume of a few crops, most of which are used for animal production.

(3) Sustainably intensify food production to increase high-quality output. The current global food system is unsustainable and requires an agricultural revolution that is based on sustainable intensification and driven by sustainability and system innovation. This change would entail reducing yield gaps on cropland, radical improvements in the efficiency of fertiliser and water use, recycling phosphorus, redistributing global use of nitrogen and phosphorus, implementing climate mitigation options, including changes in crop and feed management, and enhancing biodiversity within agricultural systems.

(4) Strong and coordinated governance of land and oceans. Such governance includes implementing a zero-expansion policy of new agricultural land into natural ecosystems and species-rich forests, management policies aimed at restoring and re-foresting degraded land, establishing mechanisms of international land-use governance, and adopting a Half Earth strategy for biodiversity conservation to safeguard resilience and productivity in food production. The world's oceans need to be effectively managed to ensure that fisheries do not negatively affect ecosystems, fish stocks are used responsibly, and global aquaculture production is expanded sustainably given its effect on and linkage to both land and ocean ecosystems.

(5) At least halve food losses and waste, in line with global sustainable development goals. Substantially reducing the amount of food lost and wasted across the food supply chain, from production to consumption, is essential for the global food system to stay within its safe operating space. Technological solutions will need to be applied along the food supply chain and public policies implemented to achieve a 50% reduction in food loss and waste.

An opportunity exists to integrate food systems into international, national, and business policy frameworks aiming for improved human health and environmental sustainability. Establishing clear, scientific targets to guide food system transformation is an important step in realising this opportunity.

## Introduction

### Food, planet, and health

In the past 50 years, global food production and dietary patterns have changed substantially. Focus on increasing crop yields and improving production practices have contributed to reductions in hunger, improved life expectancy, falling infant and child mortality rates, and decreased global poverty.[1,2] However, these health benefits are being offset by global shifts to unhealthy diets that are high in calories and heavily-processed and animal source foods. These trends are driven partly by rapid urbanisation, increasing incomes, and inadequate accessibility of nutritious foods.[3,4] Transitions to unhealthy diets are not only increasing the burden of obesity and diet-related non-communicable diseases, but are also contributing to environmental degradation.[5,6] Food in the Anthropocene represents one of the greatest health and environmental challenges of the 21st century.

The international community has taken steps in recent decades to reduce hunger and improve nutrition through global agendas such as the Millennium Development Goals, the Sustainable Development Goals, and the Decade of Action on Nutrition. However, wide-scale undernutrition still exists alongside increasing prevalence of overweight, obesity, and non-communicable diseases. Low dietary quality contributes to undernutrition, overweight, and obesity, and has caused persistent micronutrient deficiencies. Globally, more than 820 million people remain undernourished,[7] 151 million children are stunted, 51 million children are wasted,[8] and more than 2 billion people are micronutrient deficient.[9] Concurrently, prevalence of diseases associated with high-calorie, unhealthy diets are increasing, with 2·1 billion adults overweight or obese[10] and the global prevalence of diabetes almost doubling in the past 30 years.[11,12] Unhealthy diets are the largest global burden of disease and pose a greater risk to morbidity and mortality than does unsafe sex, alcohol, drug, and tobacco use combined.[4] Because much of the global population is inadequately nourished (ie, undernutrition, overnutrition, and malnutrition), the world's diets urgently need to be transformed.

Food production is the largest cause of global environmental change. Agriculture occupies about 40% of global land,[13] and food production is responsible for up to 30% of global greenhouse-gas emissions[14] and 70% of freshwater use.[2,15] Conversion of natural ecosystems to croplands and pastures is the largest factor causing species to be threatened with extinction.[16] Overuse and misuse of nitrogen and phosphorus causes eutrophication and dead zones in lakes and coastal zones.[17] Environmental burden from food production also includes marine systems. About 60% of world fish stocks are fully fished, more than 30% overfished, and catch by global marine fisheries has been declining since 1996.[18] In addition, the rapidly expanding aquaculture sector can negatively affect coastal habitats, freshwater, and terrestrial systems (related to the area directly used for aquaculture and feed production).[19] Faced with the challenge of feeding about 10 billion people a healthy and sustainable diet by 2050, and with a rising number of environmental systems and processes being pushed

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*Panel 1:* Glossary

**Anthropocene**
A geological epoch that is characterised by humanity being the dominating driver of change on Earth.

**Biosphere**
All parts of the Earth where life exists, including the lithosphere (solid surface layer), hydrosphere (water), and atmosphere (air). The biosphere plays an important part in regulating the Earth system by driving energy and nutrient flow between components.

**Boundaries**
Thresholds set at the low end of the scientific uncertainty range that serve as guides for decision makers on acceptable levels of risk. Boundaries are baselines, unchanging, and not time-bound.

**Earth system**
Earth's interacting physical, chemical, and biological processes consisting of land, oceans, atmosphere, and poles, and includes Earth's natural cycles— ie, carbon, water, nitrogen, phosphorus, and other cycles. Life, including human society, is an integral part of the Earth system and affects these natural cycles.

**Food system**
All elements and activities that relate to production, processing, distribution, preparation, and consumption of food. This Commission focuses on two endpoints of the global food system; final consumption (healthy diets) and production (sustainable food production).

**Great Food Transformation**
The unprecedented range of actions taken by all food system sectors across all levels that aim to normalise healthy diets from sustainable food systems.

**Non-communicable disease**
Long-term diseases, also known as chronic diseases, which are caused by a combination of genetic, physiological, environmental, and behavioural factors. The main types of non-communicable diseases are cardiovascular diseases, cancers, chronic respiratory diseases, and diabetes.

**Planetary boundaries**
Nine boundaries, each representing a system or process that is important for regulating and maintaining stability of the planet. They define global biophysical limits that humanity should operate within to ensure a stable and resilient Earth system—ie, conditions that are necessary to foster prosperity for future generations.

**Safe operating space for food systems**
A space that is defined by scientific targets for human health and environmentally sustainable food production set by this Commission. Operating within this space allows humanity to feed healthy diets to about 10 billion people within biophysical limits of the Earth system.

**Scientific targets**
Targets that are reached through international scientific consensus, based on the latest available science, and are time-bound. The Intergovernmental Panel on Climate Change has provided scientific targets defining ranges of maximum carbon dioxide emissions allowed to remain less than different levels of average mean global temperature rise. This Commission is providing global scientific targets defining ranges of the amount and types of food groups necessary for human health and boundaries we should stay within to reduce environmental degradation due to food production at all scales.

**Science-based targets**
Targets developed through collaboration and negotiation that build on expertise and rigor used to reach international scientific consensus on an issue (eg, scientific targets set by the Intergovernmental Panel on Climate Change). These targets are used, for example, to allocate a proportion of the required global emissions reduction targets, in line with the Paris Agreement, to an individual company in a fair and transparent way. These targets differ from scientific targets because they are based on science but factor in feasibility and viability.

beyond safe boundaries by food production, methods of food production need to be urgently reviewed.

## Integrated agenda for food systems

Diets are a major link between human health and environmental sustainability.[5,6] Lose-lose diets[20] (ie, unhealthy and environmentally unsustainable) are often characterised as being high in calories, added sugars, saturated fats, processed foods, and red meats. In addition, environmental degradation resulting from these lose-lose diets might further exacerbate poor health. Negative effects include premature deaths caused by poor air quality from biomass burning for agriculture and land clearing,[21] reduced food security resulting from low yields due to changing climatic conditions,[22] diminished nutrient content of some crops due to rising atmospheric carbon dioxide concentrations,[23] and famine exacerbated by extreme weather events such as drought.[7] This Commission focuses mainly on the link between diet, human health, and environmental sustainability, whereas other *Lancet* Commissions have explored additional areas.[1,24,25]

The global food system needs to be transformed to reduce its effect on human health and environmental stability and begin reversing current trends. However, this transformation will not be achieved without people changing how they view and engage with food systems. This change in thinking should recognise the inextricable link between human health and environmental sustainability and integrate these separate concerns into a common global agenda to achieve healthy diets from sustainable food systems. The call for an integrated agenda began in the 1980s,[26] whereas the concept of healthy and sustainable food, the focus of this Commission, has only emerged in recent years.

Two major global agendas focus on human health and environmental sustainability. The UN Sustainable Development Goals (SDGs)[27] seek to end poverty, protect the planet, ensure prosperity for all, and eradicate hunger and malnourishment. This ambitious and inclusive international policy framework includes human health or environmental sustainability in most of its goals. The Paris Agreement, although focused on climate change, also addresses the effects of climate change on human health. Furthermore, reaching the Paris Agreement of limiting global warming to well below 2°C, aiming for 1·5°C, is not possible by only decarbonising the global energy system. Transitioning to food systems that can provide negative emissions (ie, function as a major carbon sink instead of a major carbon source) and protecting carbon sinks in natural ecosystems are both required to reach this goal. A revolutionary change in food systems to support human health and environmental sustainability is essential to the Paris Agreement.[28] Given the disproportionate effect of food systems on human health and environmental sustainability, these global agendas provide an unprecedented opportunity for catalysing the change in thinking that will be necessary to transform the global food system.

## Safe operating space for food systems

An integrated agenda of human health and environmental sustainability alone will not be enough to achieve the SDGs and Paris Agreement. Clear scientific targets that define healthy diets and sustainable food production are necessary to guide policy makers, businesses, and all food system actors. The Intergovernmental Panel on Climate Change (IPCC) has set scientific targets for climate, defining ranges of maximum carbon dioxide emissions allowed to remain within different levels of average global temperature rise. These emission targets have provided estimates of remaining carbon budgets and climate risks for societies, which have formed the basis for the Paris Agreement, by 195 nations. However, the 1·5–2°C Paris range is a science-based target (panel 1), agreed on through negotiations and political consensus and based on the latest scientific understanding. For the global food system, clear scientific targets do not exist. This absence of targets is a barrier for policy makers and businesses looking for guidance in achieving their food-related SDG goals and commitments under the Paris Agreement.

We can conceptualise an integrated agenda of human health and environmental sustainability for the global food system that has clear scientific targets using the concept of a safe operating space for food systems. The concept of a safe operating space for humanity, proposed by Rockström and colleagues in 2009,[29] originates from the planetary boundaries framework and is defined as "the safe operating space for humanity with respect to the Earth system and are associated with the planet's biophysical subsystems or processes". We use the planetary boundaries framework as a guide to propose a safe operating space for food systems that encompasses human health and environmental sustainability. This space is defined by scientific targets that set ranges of intakes for food groups (ie, 100–300 g/day of fruit) to ensure human health (table 1)

| | Macronutrient intake (possible range), g/day | Caloric intake, kcal/day |
|---|---|---|
| **Whole grains*** | | |
| Rice, wheat, corn, and other† | 232 (total gains 0–60% of energy) | 811 |
| **Tubers or starchy vegetables** | | |
| Potatoes and cassava | 50 (0–100) | 39 |
| **Vegetables** | | |
| All vegetables | 300 (200–600) | .. |
| Dark green vegetables | 100 | 23 |
| Red and orange vegetables | 100 | 30 |
| Other vegetables | 100 | 25 |
| **Fruits** | | |
| All fruit | 200 (100–300) | 126 |
| **Dairy foods** | | |
| Whole milk or derivative equivalents (eg, cheese) | 250 (0–500) | 153 |
| **Protein sources‡** | | |
| Beef and lamb | 7 (0–14) | 15 |
| Pork | 7 (0–14) | 15 |
| Chicken and other poultry | 29 (0–58) | 62 |
| Eggs | 13 (0–25) | 19 |
| Fish§ | 28 (0–100) | 40 |
| Legumes | | |
| Dry beans, lentils, and peas* | 50 (0–100) | 172 |
| Soy foods | 25 (0–50) | 112 |
| Peanuts | 25 (0–75) | 142 |
| Tree nuts | 25 | 149 |
| **Added fats** | | |
| Palm oil | 6·8 (0–6·8) | 60 |
| Unsaturated oils¶ | 40 (20–80) | 354 |
| Dairy fats (included in milk) | 0 | 0 |
| Lard or tallow‖ | 5 (0–5) | 36 |
| **Added sugars** | | |
| All sweeteners | 31 (0–31) | 120 |

For an individual, an optimal energy intake to maintain a healthy weight will depend on body size and level of physical activity. Processing of foods such as partial hydrogenation of oils, refining of grains, and addition of salt and preservatives can substantially affect health but is not addressed in this table. *Wheat, rice, dry beans, and lentils are dry, raw. †Mix and amount of grains can vary to maintain isocaloric intake. ‡Beef and lamb are exchangeable with pork and vice versa. Chicken and other poultry is exchangeable with eggs, fish, or plant protein sources. Legumes, peanuts, tree nuts, seeds, and soy are interchangeable. §Seafood consist of fish and shellfish (eg, mussels and shrimps) and originate from both capture and from farming. Although seafood is a highly diverse group that contains both animals and plants, the focus of this report is solely on animals. ¶Unsaturated oils are 20% each of olive, soybean, rapeseed, sunflower, and peanut oil. ‖Some lard or tallow are optional in instances when pigs or cattle are consumed.

*Table 1:* **Healthy reference diet, with possible ranges, for an intake of 2500 kcal/day**

| | Control variable | Boundary (uncertainty range) |
|---|---|---|
| Climate change | Greenhouse-gas ($CH_4$ and $N_2O$) emissions | 5 Gt of carbon dioxide equivalent per year (4·7–5·4) |
| Nitrogen cycling | Nitrogen application | 90 Tg of nitrogen per year (65–90;* 90–130†) |
| Phosphorus cycling | Phosphorus application | 8 Tg of phosphorus per year (6–12;* 8–16†) |
| Freshwater use | Consumptive water use | 2500 km³ per year (1000–4000) |
| Biodiversity loss | Extinction rate | Ten extinctions per million species-years (1–80) |
| Land-system change | Cropland use | 13 million km² (11–15) |

*Lower boundary range if improved production practices and redistribution are not adopted. †Upper boundary range if improved production practices and redistribution are adopted and 50% of applied phosphorus is recycled.

***Table 2:*** **Scientific targets for six key Earth system processes and the control variables used to quantify the boundaries**

and planetary boundaries for food production to ensure a stable Earth system. These boundaries include the total global amount of cropland use, biodiversity loss, water use, greenhouse-gas emissions, and nitrogen and phosphorus pollution that can be due to food production (table 2). These boundaries for human health and food production identify the safe operating space within which food systems should jointly operate to ensure that a broad set of universal human health and environmental sustainability goals are achieved.

Boundaries that define a safe operating space for food systems are difficult to set in complex systems, and need to be refined over time. The Earth system and human biology are complex adaptive systems, characterised by interactions and feedback loops. All scientific targets for a safe operating space for healthy diets and sustainable food production are therefore associated with uncertainty. By applying a precautionary and risk perspective, boundaries are placed at the lower end of the scientific uncertainty range, establishing, with a high likelihood, a safe space in which food systems can operate.[30] These boundaries should be viewed as guides for decision makers on acceptable levels of risk for human health and environmentally sustainable food production. Operating outside this space for any Earth system process (eg, high rates of biodiversity loss) or food group (eg, insufficient vegetable intake) increases risk for harm to the stability of the Earth system and human health. When viewed together as an integrated human health and environmental sustainability agenda, win-win diets,[20] that fall within the safe operating space for food systems, will help to achieve global human health and environmental sustainability goals.

## Scope and limitations

This Commission brings together scientists from several disciplines to assess the global food system and set global scientific targets for shifting the world towards healthy diets and sustainable food production. Because setting such targets can be difficult, this Commission focuses on two endpoints of the global food system: final consumption (healthy diets) and production (sustainable food production). These factors disproportionately affect human health and environmental sustainability; however, the food system is not only affected by these two endpoints. Throughout the Commission we use the term food system and acknowledge that food systems are not limited to food production and consumption. Food systems are comprised of all the elements (eg, environment, people, inputs, processes, infrastructures, and institutions) and activities that relate to the production, processing, distribution, preparation and consumption of food.[31] By referring to the food system throughout the Commission, our intention is to emphasise that the Great Food Transformation can only be achieved with all actors in all parts of the food system working collectively towards this transformation. Furthermore, we acknowledge that food systems also affect society, culture, economy, and animal welfare. However, given the breadth and depth of the topics discussed, many important issues could not be discussed. These and other issues should be considered to achieve healthy diets from sustainable food systems.

This Commission is not setting actionable science-based targets (panel 1) on behalf of any country, sector, or business, nor does it have a mandate to do so. This Commission is an independent scientific body using the latest available science to make a global assessment of the food system and set global scientific targets for healthy diets and sustainable food production. These targets form the first attempt to provide scientific guidance for a transformation towards healthy diets from sustainable food systems. The goal, in the absence of an intergovernmental scientific panel or comprehensive agreement for food, is for science to continue refining definitions of global scientific targets for human health and environmentally sustainable food production while business and policy makers begin translating these definitions into operational science-based targets for various sectors, regions, and countries.

The planetary boundaries framework expands the definition of sustainable food production to include the global nature of food production's environmental effects, connecting local to global scales. However, this framework does not provide a plan for translating global targets to national and subnational governments, businesses, and other local actors. This approach is intended to inform national, sectoral, and sociopolitical targets and prioritisations, highlighting the global environmental context within which these diverse activity areas should fit. This approach becomes a first step in connecting a planetary perspective with context-specific levels of action.

In this Commission, we do not propose a simple global fix to the problems discussed. The safe operating space for food systems will require implementation of a variety and multitude of solutions and innovations. For food production, we avoid comparing specific production systems (eg, organic *vs* conventional) because numerous comparisons exist[32] and debates about specific production systems and diets can be overly prescriptive and mask diversity of contexts and available solutions. We give guidance on healthy diets but provide sufficient scope for many global dietary patterns (eg, vegetarian and pescatarian) to be considered. This scope is captured by use of broad food groups and intake ranges that allow for various dietary preferences to be considered. Guaranteed solutions neither exist nor would allow users of this analysis to adopt a holistic concept of a safe operating space for food systems that will be needed.

This Commission does not explore various population growth scenarios, such as the Shared Socioeconomic Pathways. A major driver of increasing requirements for food is a growing global population, which is expected to increase from about 7·6 billion people in 2017, to 9·8 billion people in 2050. Reducing the rate of population growth will therefore be essential for achieving healthy and sustainable diets for the world's population. Universal access to sexual and reproductive health-care services (including family planning), information, and education will be necessary components of this goal. Our analysis follows the Shared Socioeconomic Pathway 2 for a moderate population growth (9·2 billion people), and trends (ie, population growth, GDP) broadly follow historical patterns (appendix p 1).

Lastly, although this Commission uses 2050 as a cutoff, the issues discussed extend beyond 2050. Global population is expected to exceed 11 billion people by 2100 unless actions are taken to stabilise population growth (appendix p 2). Healthy diets from sustainable food systems are possible for up to 10 billion people but becomes increasingly unlikely past this population threshold.

### Treatment of uncertainty

Few decisions about diet, human health, and environmental sustainability can be made on the basis of absolute certainty because evidence is incomplete, imperfect, and continually evolving; therefore, certainty should be considered as a continuum. We have attempted to base estimates on the best available science, and we acknowledge that uncertainty exists. Therefore, when possible, we acknowledge this uncertainty and our confidence in the validity of our findings and qualitatively discuss this on the basis of the type, quantity, quality, and consistency of evidence. We have a high level of scientific certainty about the overall direction and magnitude of associations described in this Commission, although considerable uncertainty exists around detailed quantifications. Modelling and sensitivity analysis provide ways to explore the implications of this uncertainty.

## Section 1: Healthy diets

### What is a heathy diet?

Defining healthy dietary patterns is important for many reasons. For example, they are used to provide dietary guidance to a population, provide assessment and counselling in clinical settings, develop practices and policies designed to enhance diet, and monitor trends in diet quality for an individual or a population. However, practical considerations make defining a global healthy diet challenging. These difficulties include different nutritional needs of people because of age, sex, disease status, and physical activity levels, and needs of vulnerable populations (ie, young children and pregnant women).

A healthy diet should optimise health, defined broadly by WHO as being a state of complete physical, mental, and social wellbeing, and not just absence of disease. We focus on diets for generally healthy individuals aged 2 years and older. Young children (aged 0–2 years) have unique requirements to support rapid growth and development, but their diets have only minor effects on food systems because they constitute a small proportion of a stable population and have low absolute food requirements. Because animal source foods can have important effects on human health and environmental sustainability, detail will be given to these foods. The conclusions of this section are based only on health outcomes. Although important, we do not consider food safety (ie, microbial or other forms of contamination).

We define a healthy diet using food groups while taking into consideration nutritional adequacy because this most directly connects food production and health, and because most dietary guidelines are based primarily on food groups. However, a focus exclusively on food groups does not incorporate added fats, sugar, salt, and other constituents, so these will also be considered. The definition of a healthy diet is based on evidence from controlled feeding studies in humans with intermediate risk factors as outcomes, observational studies, and randomised trials. Where available, we cite systematic reviews, meta-analyses, and pooled analyses of primary data (appendix pp 4–12). Extensive reviews documenting the importance of dietary quality have been published elsewhere.[33,34]

See Online for appendix

The healthy dietary pattern we propose consists of ranges of intakes for each food group. This pattern allows for flexible, global application of these criteria (table 1), with foods and amounts tailored to preferences and cultures of different populations (panel 2).

### Uncertainty in estimates of a healthy diet

We have a high level of confidence, based on many reproducible lines of evidence, that the reference diet that we have defined will meet nutritional requirements for children older than 2 years and adults, and reduce the incidence of non-communicable diseases and overall mortality. Optimal quantities of specific food groups are often less clear partly because they depend on intakes of other dietary components. Additionally, for some food groups, the association between intake and health risks is approximately linear, making specification of optimal intake difficult. Although a linear positive association would suggest an optimal intake of zero, an effect of zero intake with an adverse outcome is not possible to distinguish from that of a small intake. Furthermore, all

***Panel 2:* Feasibility of reference diet**

Although the reference diet, which is based on health considerations, is consistent with many traditional eating patterns, for some individuals or populations this diet might seem extreme or not feasible. However, from a global perspective the features of this diet, which could include strict vegetarian diets and consumption of modest amounts of animal source foods, have well established traditions in various regions. The best studied example is the Mediterranean diet, similar to the diet of Crete in the mid-20th century. This diet was low in red meat (average intake of red meat and poultry combined was 35 g/day)[A1] and largely plant-based, but high in total fat intake (about 40% of energy) consumed mainly as olive oil.[A2] Greeks had one of the longest life expectancies at the time.[A3]

Many other traditional diets, such as those in Indonesia, Mexico, India, China, and West Africa, also include little red meat, which might be consumed only on special occasions or as minor ingredients of mixed dishes.[A4–6] Some of these cultures have also consumed few or no dairy foods, often corresponding with lactose intolerance and lower rates of bone fracture than have countries with high dairy consumption.[A7] High consumption of nuts is traditional in some West African populations (ie, about 100 g/day in Niger) and large amounts of soy foods are consumed in many Asian populations (ie, 46 g/day in Taiwan).[A5] Legume consumption has traditionally been high in many cultures, such as Mexico, India, and Rwanda.[A4,A8] Thus, ample precedent exists for the ranges of food intakes represented by the reference diet, and the culinary experiences of different regions provide many opportunities to learn new ways of preparing diets that are healthy and enjoyable.

References cited in this panel can be found in the appendix (p 27)

food groups in a diet need to fit within a constrained total energy intake. To make calculations possible for total nutrient intakes, health effects, and environmental effects for overall diets, we provide a number for each food group of the healthy reference diet. We also provide an uncertainty range (upper and lower limits) that appears to be compatible with optimal health and within consumption ranges of at least some populations globally because this provides some evidence of long-term safety. In subsequent analyses, we use alternative values for some key food groups for sensitivity analyses. Using several approaches, we estimate the effect of the reference diet on premature mortality. We anticipate further research will provide improved precision in defining ranges for optimal intakes of specific food groups and health effects of overall diets.

## Status of knowledge

*Energy and energy balance*

The global average per capita energy intake has been estimated as 2370 kcal per day.[30] In a rigorous and large pooled analysis[35] of adults from the USA, energy intake was about 2800 kcal per day for men and 2000–2200 kcal per day for women. Energy intake would be lower in populations with lower body-mass index (BMI; calculated as kg/m²) and higher in populations with greater physical activity. We have therefore used 2500 kcal per day as a basis for different isocaloric dietary scenarios (ie, having similar caloric values). Consuming 2500 kcal per day corresponds to the average energy needs of a 70-kg man aged 30 years and a 60-kg woman aged 30 years whose level of physical activity is moderate to high. This energy intake is higher than the intake of 2100 kcal/day used in other analyses that assumed a BMI of about 22, which is substantially lower than the global average BMI. Although an average BMI of 22 would be healthier than population averages, effective means of reversing the obesity epidemic in many countries have not been identified. Thus, assuming this BMI and a lower energy intake is risky and would leave little room for public health goals to increase physical activity because this will require additional food energy. Although use of different values for energy intake would affect absolute required food production, it would minimally affect conclusions regarding relative effects of different dietary scenarios on environmental or health outcomes.

## Dietary components

*Major protein sources*

Adequate protein intake for adults is 0·8 g/kg bodyweight, which is 56 g/day for a 70-kg individual or about 10% of energy intake. Protein quality (defined by effect on growth rate) reflects the amino acid composition of the food source, and animal sources of protein are of higher quality than most plant sources. High-quality protein is particularly important for growth of infants and young children, and possibly in older people losing muscle mass in later life. However, a mix of amino acids that maximally stimulate cell replication and growth might not be optimal throughout most of adult life because rapid cell replication can increase cancer risk.[36]

Protein can have indirect beneficial metabolic effects by replacing excessive carbohydrate intake, especially if this intake is refined starch and sugar. In a large controlled feeding trial,[37] replacing carbohydrate isocalorically with protein reduced blood pressure and blood lipid concentrations. Similar effects were seen with monounsaturated fat replacing carbohydrate, suggesting that benefits were due to reduced carbohydrate intake.

Because protein is consumed as a part of foods that contain fat and many other constituents that affect health, protein food sources, or packages, should be considered when investigating or making food choices. Although most foods contain some protein, meat, dairy, fish, eggs, legumes (including soy), and nuts (including peanuts) are high in protein and often considered as alternatives to one another in many culinary traditions. These major protein sources are also commonly used to define diets, such as omnivore, vegetarian, pescatarian, or vegan.

In a review,[33] the 2015 US Dietary Guidelines Advisory Committee concluded that for people older than 2 years, a balanced vegetarian diet can be a healthy eating pattern. In the largest prospective study[38] of vegetarian diets, people following vegan, vegetarian, pescatarian, or semi-vegetarian diets had 12% lower overall mortality risk than did omnivores; the lowest risk was among pescatarian diets.[38] Using another approach, a plant-based dietary score (assigning positive values to the consumption of healthy plant-based foods, but not refined grains or sugar, and negative values to animal-sourced foods) was inversely and linearly associated with risk of type 2 diabetes and coronary heart disease.[39,40] These findings suggest that a shift towards a dietary pattern emphasising whole grains, fruits, vegetables, nuts, and legumes without necessarily becoming a strict vegan, will be beneficial.

Most analyses of foods high in protein and health outcomes have not specified any comparison food. Thus, in an isocaloric analysis, the comparison food becomes the mix of foods comprising the rest of the diet, to which refined carbohydrates (eg, white bread, polished rice, or corn and sugar) are typically the major contributors. Despite this limitation, in a meta-analysis of prospective studies,[41] consumption of processed red meat (beef, pork, or lamb) was associated with increased risk of death from any cause and cardiovascular disease; unprocessed red meat was also weakly associated with cardiovascular disease mortality. Although data were scarce, consumption of white meat (poultry and fish) was not associated with increased mortality. In other meta-analyses, consumption of red meat was associated with increased risk of stroke[42] and type 2 diabetes.[43] In two large studies,[44–46] red meat (processed and unprocessed) was linearly associated with total mortality, and without a threshold, suggesting that optimal intake would be low (appendix p 2). In a pooled analysis of three large cohorts, an increment of about 35 g/day of red meat was associated with a significant increase (6%) in risk of type 2 diabetes, and this association was also approximately linear.[47]

Other analyses have compared different protein sources with risk of additional important health outcomes. Although consumption of red meat was only weakly associated with increased risk of coronary heart disease when compared with the rest of the diet, red meat was clearly associated with increased risk of coronary heart disease when specifically compared with consumption of poultry and fish, and especially nuts and legumes. Similar associations have been seen in analyses with type 2 diabetes, stroke, and total mortality (appendix p 2).[44,45] Low intake of red meat is consistent with traditional Mediterranean diets that have been associated with exceptional longevity (panel 2). In the 1960s, when incidence of coronary heart disease and overall mortality was low in Greek men living in Crete, their average intake of red meat and poultry combined was 35 g/day.[48]

Based on evidence related to colorectal cancer, processed red meat (eg, treated with salt or other preservatives) was determined by the International Agency for Research on Cancer review to be a group 1 carcinogen, and because data were less consistent, unprocessed red meat was classified as a group 2 carcinogen. Consumption of other major protein sources during midlife and later has not been clearly related to other types of cancer, compared with a low intake of red meat during adolescence[49] and early adult life,[50] high intake has been associated with an elevated risk of breast cancer.

In a prospective cohort analysis,[51] protein intakes from food sources were assessed in relation to total and cause-specific mortality among 131 000 men and women followed up with repeated measures of diet for up to 32 years. Replacing protein from animal sources with protein from plant sources was associated with substantially reduced overall mortality. Hazard ratios were 0·66 (95% CI 0·59–0·75) when 3% of energy from plant protein replaced an equivalent amount of protein from processed red meat and 0·88 (0·84–0·92) from unprocessed red meat.

High risks of cardiovascular disease and other outcomes associated with high consumption of red meat are probably partly due to multiple food constituents of animal sources of protein. The high ratio of saturated to polyunsaturated fat and high levels of heat-induced carcinogens and haem iron might contribute to higher risks of cardiovascular disease, diabetes, and some cancers in people who eat red meat than in people who eat plant sources of protein.[46] Notably, essential polyunsaturated fatty acids comprise only 4% of lipids in beef tallow, but 21% in chicken fat, and 40% in salmon fat. The composition of processed meats is heterogeneous, but many contain high amounts of sodium, nitrates, nitrites, and other preservatives that might add to cancer risks.

Most of the available evidence has been from studies done in Europe and the USA. In a pooled analysis of Asian cohort studies,[52] poultry and red meat consumption (mainly pork) was inversely associated with all-cause mortality. The discrepancies between this analysis and those from Europe and the USA might be partly explained by the fact that Asian populations eat smaller amounts of meat than European and American populations. The authors noted that the findings could be due to confounding factors because meat might be more available to individuals of high socioeconomic status, who also have better overall health, than those of low socioeconomic status. Because many Asian countries have only recently become affluent (ie, past 10–20 years), current red meat intake does not reflect long-term intakes; like for smoking, many decades are needed to show the full health consequences of high consumption. Among Chinese people living in Singapore, which has been affluent for several decades, red meat consumption has been associated with risk of type 2 diabetes[47,53] However, in low-income populations in which the majority of energy comes from starchy carbohydrates, the addition of meat or other major protein sources is likely to mitigate micronutrient deficiencies and have metabolic benefits by reducing high glycaemic load (panel 3).

Because intake of red meat is not essential and appears to be linearly related to total mortality and risks of other health outcomes in populations that have consumed it for many years, optimal intake might be 0 g/day, especially if replaced by plant sources of protein. Because data on risk of low intakes of red meat are imprecise, we have concluded that an intake of 0 g/day to about 28 g/day of red meat is desirable and have used a midpoint of 14 g/day for the reference diet. Since consumption of poultry has been associated with better health outcomes than has red meat, we have concluded that the optimum consumption of poultry is 0 g/day to about 58 g/day and have used a midpoint of 29 g/day for the reference diet (table 1).

High intake of dairy products, at least three servings per day, has been widely promoted in western counties for bone health and fracture prevention, primarily because of their high calcium content. However, the optimum calcium intake remains uncertain. Recommendations in the USA of 1200 mg/day are derived from balance studies lasting 3 weeks or less,[54] which probably reflect transient movements of calcium in and out of bone rather than long-term requirements. A WHO review, noting that regions with low intake of dairy foods and calcium have lower fracture rates than regions with high dairy consumption,[55] concluded that 500 mg/day is adequate and lower intakes might be adequate in areas with low fracture rates. The UK has concluded that 700 mg/day is an adequate intake.[56] These lower amounts for adequate intake (compared with the USA) have major implications for dietary recommendations because many foods contain modest amounts of calcium, and eating a wide variety of diets with no dairy foods will include 300–400 mg of calcium. Although prospective studies have been heterogeneous, overall evidence suggests that among adults, risk of fractures is not substantially reduced with calcium intakes greater than 500 mg/day.[57] One 250 g serving of milk per day contains about 300 mg of calcium. This reference diet contains 718 mg/day of calcium.

Data on dairy consumption during childhood and adolescence and long-term health outcomes are scarce, but high intake might be particularly important because of skeletal growth. However, high consumption of milk in adolescent girls was not associated with reduced risk of hip fracture later in life, and in adolescent boys, high milk consumption was associated with increased risk of fractures.[58]

Prospective studies do not show a significant increase or decrease in risk of overall mortality or cardiovascular disease with increasing consumption of dairy foods,[59] although overall and cardiovascular mortality is likely to decrease if dairy foods are replaced with nuts and other plant sources of protein.[51] High milk consumption, probably because of its calcium content, is associated with reduced risk of colorectal cancer,[60] but also increased risk of prostate cancer in men,[61] especially advanced cases.[62] Some evidence suggests that yoghurt might reduce risk of diabetes and weight gain.[63,64] Although low-fat dairy foods might be preferable to high-fat dairy foods for health, nearly all the fat in milk that is produced remains in the human food supply, often as butter or cream. Thus, low-fat dairy products will have little overall effect on population health because fat is consumed in other forms.

Because a clear association does not exist between intake of milk or its derivatives greater than 0–500 g/day and major health outcomes, and competing risks for some types of cancer, a wide range of intakes are compatible with good health. Because consumption of unsaturated plant oils conveys lower risks of cardiovascular disease than does dairy fat, optimal intake will usually be at the lower end of this range, and we have used 250 g/day for the reference diet.

Fish intake has been associated with reduced risk of cardiovascular disease.[65,66] Fish has a high content of

### *Panel 3:* Animal source foods in sub-Saharan Africa

People in sub-Saharan Africa are some of the most nutritionally insecure on the planet. About 220 million people have inadequate nutrition.[A9] Despite micronutrient supplementation programmes, the burden of multiple micronutrient deficiencies, as well as anaemia and stunting, remains high. Although several countries have substantially reduced the proportion of people who are starving and whose growth is stunted (ie, Rwanda 44% to 24·5%; Uganda 38·3% to 29%; Ghana 46% absolute decline; Tanzania 50% to 34%; Malawi 53% to 37%), declines in children who are stunted in Africa have been marginal—from 38% in 1990 to 34% in 2008.[A10] Of the 36 countries with the highest burden of stunting among children younger than 2 years, 21 (58%) are in Africa, and 40% or more children in most of those countries are stunted. This undernutrition is sometimes associated with low consumption of animal source and other protein rich foods.[A11]

Because carbohydrate intake is high in many parts of sub-Saharan Africa, promotion of animal source foods for children, including livestock products, can improve dietary quality, micronutrient intake, nutrient status, and overall health.[A12–15] In observational studies, high intake of animal source foods has been associated with improved growth, micronutrient status, cognitive performance, and motor development, and increased activity in children.

However, per-capita consumption of animal source foods in sub-Saharan Africa has decreased in the past few decades and remains low at about 164 kcal/capita per day (Zambia), compared with 995 kcal/capita per day in the USA. Based on projections by the Food and Agricultural Organization, availability of animal source protein across sub-Saharan Africa will only be 13 g/person per day in 2050, which is less than half of the world average of animal source protein availability in 2011 and less than the recommended quantity in our healthy reference diet (table 1).

Because many regions, such as sub-Saharan Africa, still face severe burdens of undernutrition and malnutrition, and growing children often do not obtain adequate quantities of nutrients from plant source foods alone,[A16–19] the role of animal source foods should be examined carefully. Achieving healthy diets from sustainable food systems for everyone on the planet is possible; however, to accomplish this goal, local and regional realities need to be carefully considered.

References cited in this panel can be found in the appendix (p 27).

omega-3 fatty acids, which have many essential roles, including being precursors of eicosanoids, a large component of the CNS, a structural element of every cell of the body, and a regulator of cardiac rhythm. Eating about 2 g/week of omega-3 fatty acids in fish, equal to about one or two servings of fatty fish a week, might reduce the chances of dying from heart disease by more than a third.[65]

Fish that are high on the food chain can bioconcentrate mercury, which has neurological toxicity. Mercury concentrations are high in king mackerel, shark, swordfish, tuna, and tilefish, which should be avoided by pregnant and lactating women. However, adequate intakes of omega-3 fatty acids are essential for neurodevelopment, and eating more than two servings of fish per week or taking fish oil supplements during pregnancy has been associated with improved child cognitive performance.[67] Mercury toxicity can be avoided by consuming small fish, and omega-3 fatty acids from plant sources (specifically α-linolenic acid) have been associated with reduced risk of coronary heart disease.[68] The degree to which omega-3 fatty acids from plant sources can substitute omega-3 fatty acids from fish for other health outcomes is important to determine because plant sources are more widely available.

About 28 g/day of fish can provide essential omega-3 fatty acids and is associated with reduced risk of cardiovascular disease; therefore, we have used this intake for the reference diet. We also suggest a range of 0–100 g/day because high intakes are associated with excellent health. Plant sources of α-linolenic acid can provide an alternative to omega-3 fatty acids, but the quantity required is not clear.

Eggs are a widely available source of high-quality protein and other essential nutrients needed to support rapid growth. Despite past concern about possible increases in risk of heart disease because of their high content of cholesterol, in large prospective studies[69] high consumption of eggs, up to one a day, has not been associated with increased risk of heart disease, except in people with diabetes. However, the default comparison in these studies has been the remaining typical diet, which is often far from ideal. Isocaloric substitution of plant protein sources for eggs might therefore reduce risk of non-communicable diseases. However, in low-income countries, replacing calories from a staple starchy food with an egg can substantially improve the nutritional quality of a child's diet and reduce stunting.[70] We have used an intake of eggs at about 13 g/day, or about 1·5 eggs per week, for the reference diet, but higher intake might be beneficial for low-income populations with poor dietary quality.

Nuts, including peanuts, are nutrient-dense and contain primarily unsaturated fatty acids, fibre, vitamins, minerals, antioxidants, and phytosterols. In observational and intervention studies[71,72] nut consumption reduces blood lipid concentrations, oxidative stress, inflammation, visceral adiposity, hyperglycaemia, and insulin resistance. In a meta-analysis of 25 controlled feeding studies,[72] participants were fed an average of 67 g/day of nuts; blood concentrations of LDL cholesterol and triglycerides and the LDL cholesterol to HDL cholesterol ratio were reduced in a dose-response manner. In prospective studies, high consumption of nuts has been associated with reduced risk of cardiovascular disease,[73–75] type 2 diabetes, and overall mortality.[76,77] In the Spanish PREDIMED trial,[78] people randomly assigned to 30 g of mixed nuts per day as part of a Mediterranean diet had a 28% reduction in cardiovascular disease risk.[78] Despite being an energy-dense food, nut consumption strongly induces satiety and is associated with no weight gain (or reduced weight) and reduced risk of obesity in observational studies and clinical trials.[73] As an alternative to red meat, for the reference diet we use an intake of 50 g/day of nuts, which can include peanuts and tree nuts. These and other plant protein sources are generally exchangeable, although a mix is desirable nutritionally.

Legumes have reduced concentrations of LDL-cholesterol and blood pressure in controlled feeding studies.[79] In prospective studies,[74,80] consumption of legumes has been associated with lower risks of coronary heart disease than has consumption of red meat; however, the 95% CIs have been wide because legume consumption was low. Soybeans have a high fat content, which is largely polyunsaturated, and a high concentration of α-linolenic acid. High concentrations of phytoestrogens in soy foods have weak oestrogenic effects, which might block actions of endogenous oestrogens, and thus reduce risk of breast cancer and other hormonally-related cancers. In the Shanghai Women's Health Study,[81] consumption of soy foods during childhood and early adult life was inversely associated with risk of premenopausal breast cancer. Given this association, we included 50 g dry weight per day of beans, lentils, and peas, and 25 g/day of soy beans in the reference diet.

Other protein sources such as insects, which are important in some traditional diets, are being considered for widespread consumption. These alternatives might have little effect on the environment, but their long-term health effects have not been studied. Cyanobacterium (ie, blue-green algae) has traditionally been consumed in some cultures and has a high protein content and a similar amino acid profile to egg.[82] In-vitro meat production from cultured animal stem cells is being developed as an alternative to traditional meat.[83] The health effects of these new foods are unclear, but nutritional composition of in-vitro meat is more readily modifiable than that of conventional meat.

*Major carbohydrate sources (grains and tubers)*

Grains are the largest source of energy in almost all diets worldwide. Refining grains causes major loss of nutrients and fibre, which has important health implications. High intake of whole grains and fibre from grain sources has been associated with reduced risk of coronary heart disease, type 2 diabetes, and overall mortality.[84] Few studies have examined associations between total or refined grains and health outcomes, but refined grains are a major source of high-glycaemic carbohydrates, which have adverse metabolic effects and are associated with increased risk of metabolic abnormalities, weight gain, and cardiovascular disease.[64,85] In a prospective international study,[86] done mainly in low-income and middle-income countries, total carbohydrate intake accounting for more than 60% of energy, was associated with increased total mortality. In controlled feeding studies,[37,87] high carbohydrate intake increases blood triglyceride concentration, reduces HDL cholesterol concentration, and increases blood pressure, especially in individuals with insulin resistance. These findings are of global significance because declining levels of physical activity and increasing adiposity will raise insulin resistance and exacerbate these metabolic responses to carbohydrate intake, and thus increase the risk of cardiovascular disease and diabetes.[88,89]

Potatoes, although containing large concentrations of potassium and some other vitamins, provide a large amount of rapidly absorbed carbohydrate, or glycaemic load. Daily consumption has been associated with increased risk of type 2 diabetes,[90] hypertension,[91] and weight gain.[92] Globally, cassava is grown for its resilience in semi-arid conditions, but when processed into flour, as is done in Africa, it has low nutritional value and high glycaemic load, which might increase metabolic abnormalities, weight gain, and cardiometabolic disease.

We use major carbohydrate sources to maintain target energy intake. Evidence does not suggest a specific proportion of energy intake from carbohydrates, but keeping this to less than 60% of energy appears desirable, and consumption of whole grains is emphasised. Thus, we use 232 g/day of whole grains and 50 g/day of tubers and starchy vegetables (with a limit of 100 g/day of tubers and starchy vegetables).

### *Fruits and vegetables*

Fruits and vegetables are an essential source of many micronutrients, including provitamin A for prevention of night blindness. Substantial evidence indicates that fruit and vegetable consumption is also important for prevention of cardiovascular disease; benefit is mostly achieved by consuming about five servings per day,[93,94] although higher intakes might provide some benefits. High intake of vegetables reduces blood pressure[95] and is associated with reduced risk of type 2 diabetes.[96] Increasing intake of most non-starchy vegetables has been associated with reduced weight gain in long-term follow-up of adults in the USA,[92] but intakes of potatoes, corn, and peas were each associated with increased weight gain. High fruit and vegetable consumption is weakly associated with reduced cancer incidence after adjusting for differences in other lifestyle factors such as smoking and BMI.[97,98]

We use intakes of 300 g/day of vegetables and 200 g/person per day of fruits, or about five servings of fruits and vegetables each day. Most benefit from these foods is probable if a mix is included as suggested.

### *Added fat: total and specific fatty acids and sources of fats*

Added fats from animal sources (eg, ghee, butter, and lard) or plants (eg, oils, margarines, and shortening) are used in countless recipes and in cooking of many foods; they can comprise up to about 30% of total energy in some diets. Most dietary recommendations suggest reducing or limiting total fat intake to decrease risks of coronary disease and cancer. However, evidence from prospective cohort studies and randomised trials has not suggested a benefit of reducing total fat intake.[99,100] Evidence supports a substantially reduced risk of cardiovascular disease by replacing saturated fat with unsaturated vegetable oils, especially those high in polyunsaturated fats that include omega-3 and omega-6 fatty acids.[99,101–103] Intake of trans isomers from partly hydrogenated oils is particularly deleterious.[104]

Although intakes of specific fatty acids have been studied extensively in relation to risk of heart disease, edible oils are always a combination of saturated, monounsaturated, and polyunsaturated fatty acids, depending on the source and processing. Palm and soybean oil are the most widely consumed oils globally. Compared with soybean oil, palm oil is low in polyunsaturated fat (9% *vs* 60%) and high in saturated fat (52% *vs* 16%), and is widely consumed in many low-income and middle-income countries. Consistent with this fatty acid composition, consumption of industrially processed palm oil raises LDL-cholesterol compared with less saturated plant oils.[105] In a case-control study[106] done in Costa Rica, consumption of industrially processed palm oil was significantly associated with greater risk of myocardial infarction than was nonhydrogenated soy bean oil. In many West African countries and parts of Brazil, minimally processed red palm oil is an important source of provitamin A because of its high β-carotene content. Consumption of red palm oil has not been studied in relation to risk of heart disease and moderate intake might be compatible with low rates of heart disease.

In the PREDIMED trial,[78] compared with a low-fat diet, a Mediterranean diet high in extra virgin olive oil reduced incidence of cardiovascular disease and improved cognitive function. Rapeseed oil, also called canola oil, is high in monounsaturated fats and contains a substantial amount of omega-3 fatty acids. In a randomised trial among survivors of acute myocardial infarction, a Mediterranean-type diet high in rapeseed oil greatly reduced risk of recurrent infarction or death.[107] In the most successful national programme to reduce rates of coronary heart disease (Finland), rapeseed oil was used to replace dairy fat.[108] Dairy fat has one of the highest proportions of saturated fatty acids in natural foods. In a detailed prospective analysis[109] among men and women, when compared isocalorically, dairy fat was associated with greater risk of coronary heart disease than was unsaturated plant oils.

Low-fat diets have been widely promoted for weight loss or prevention of weight gain. Most of the randomised trials[110] were less than 1 year in duration, which can be misleading because initial reductions in weight are often reversed. Furthermore, the intensity of intervention was not balanced in many trials,[111] which is important because monitoring intake and social support can lead to modest reductions in weight independent of dietary composition.[112] In a meta-analysis[113] including more than 50 randomised trials lasting at least 1 year, reductions in dietary fat were associated with slightly less weight loss than was the high-fat control diet when intensity of intervention was similar.

Evidence supports consumption of plant oils low in saturated fat as an alternative to animal fats; however, no clear upper limit of consumption exists. Thus, a wide range is suggested, and we use 50 g/day of total added fat with a mix emphasising predominately unsaturated plant oils.

#### *Sugar and other sweeteners*

Sugar, like refined starches, has multiple adverse metabolic effects, and at high intakes might further increase plasma triglyceride concentrations.[114] High intakes of added sugars, especially sugar-sweetened beverages, have been associated with weight gain,[115,116] type 2 diabetes,[117] and increased cardiovascular mortality.[118] WHO recommends that sugar intake be less than 10% of energy and suggests that reducing to 5% would provide further benefits; the American Heart Association suggests approximately 5% of energy or less. Because sugar has no nutritional value and adverse metabolic effects, we use a limit of 31 g/person per day of all sweeteners, or less than 5% of energy.

### Special considerations

#### *Young children and adolescents*

Global and most regional guidelines recommend that infants should be exclusively breastfed for the first 6 months of life and continued breastfeeding until at least age 2 years. Benefits include healthy growth and expected cognitive development as well as possibly reduced risk of becoming overweight or obese and developing non-communicable diseases later in life.[119,120] For children aged 12–23 months, whether breastfed or not, a diet with daily inclusion of at least four of seven food groups has been recommended.[121]

Adolescent girls are at risk of iron deficiency because of rapid growth combined with menstrual losses. Menstrual losses have sometimes been a rationale for increased consumption of red meat, but multivitamin or multi-mineral preparation provide an alternative that is less expensive and without adverse consequences of high red meat intake. WHO suggests extra iron for adolescent girls by supplementation where the prevalence of anaemia is high, with extra caution in malaria endemic regions.[122]

#### *Pregnancy and lactation*

During pregnancy and lactation, overall food intake is important to support organ, muscle, and bone growth, as well as sustain physiological and metabolic health. However, excessive protein intake from animal sources has been associated with an increased risk of obesity in offspring 20 years later.[123] In a systematic review,[124] maternal consumption of dairy foods was inconsistently associated with birthweight or fetal length. Although inclusion of some animal source foods in maternal diets is widely considered important for optimal fetal growth and increased iron requirement, especially during the third trimester of pregnancy, evidence suggests that balanced vegetarian diets can support healthy fetal development, with the caveat that strict vegan diets require supplements of vitamin B12.[125] WHO recommends a healthy diet during pregnancy defined as adequate energy, protein, vitamins, and minerals obtained through consumption of various foods, including green and orange vegetables, meat, fish, beans, nuts, whole grains, and fruits.[126]

### Summary of evidence describing healthy diets

Evidence from controlled feeding studies with intermediate-risk factors as outcomes, long-term observational studies relating individual dietary components and overall dietary patterns to major disease endpoints and quality of life,[127–129] and randomised clinical trials supports the conclusion, with a high level of certainty, that dietary patterns with the following characteristics promote low risk of major chronic disease and overall wellbeing: (1) protein sources primarily from plants, including soy foods, other legumes, and nuts, fish or alternative sources of omega-3 fatty acids several times per week with optional modest consumption of poultry and eggs, and low intakes of red meat, if any, especially processed meat; (2) fat mostly from unsaturated plant sources, with low intakes of saturated fats, and no partly hydrogenated oils; (3) carbohydrates primarily from whole grains with low intake of refined grains and less than 5% of energy from sugar; (4) at least five servings of fruits and vegetables per day, not including potatoes; and (5) moderate dairy consumption as an option.

These elements of a healthy diet allow great flexibility because they are compatible with a wide variety of foods, agricultural systems, cultural traditions, and individual dietary preferences. These elements can be combined in various types of omnivore, vegetarian, and vegan diets. The findings of benefits in many populations for overall dietary patterns, such as the Mediterranean and healthful plant-based diets, show that healthy dietary patterns can be achieved in contemporary populations in many countries. The intakes in table 1 provide a starting point for further analyses to evaluate the potential for feeding the world's population a healthy diet while remaining within food production boundaries (panel 2).

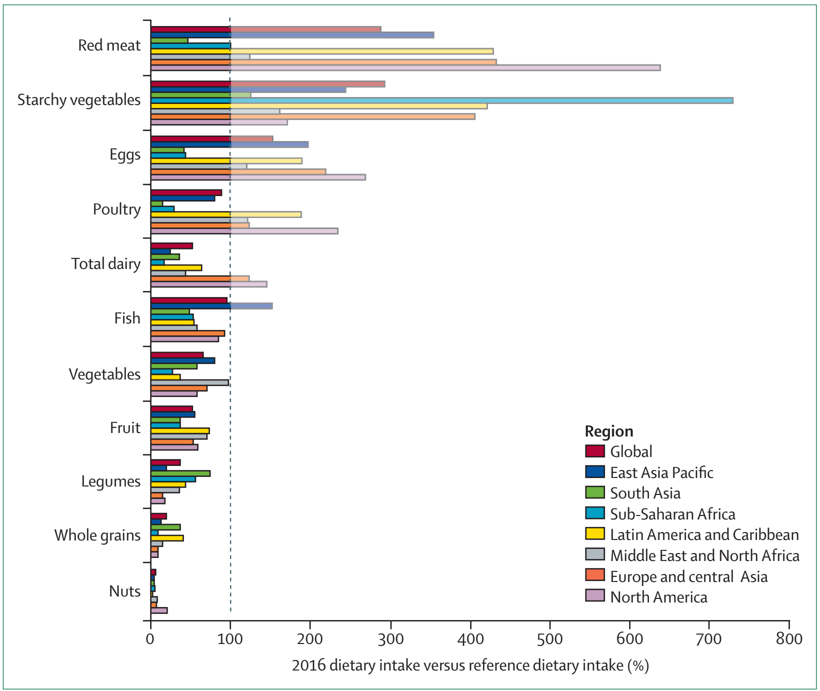


*Figure 1:* **Diet gap between dietary patterns in 2016 and reference diet intakes of food**
Data on 2016 intakes are from the Global Burden of Disease database.[130] The dotted line represents intakes in reference diet (table 1).

| | Percentage | Number | Comments |
|---|---|---|---|
| Comparative Risk Model* | 19% | 11 100 000 (using Global Burden of Disease number of total deaths; 158 regions) | Changes in fruits, vegetables, nuts, and legumes were main contributors |
| Global Burden of Disease Model† | 22·4% | 10 886 000 (195 countries) | Changes in sodium, fruits, vegetables, whole grains, and nuts were main contributors |
| Empirical Disease Risk‡ | 23·6% | 11 600 000 (190 countries) | Estimates based on a 10-variable index of diet quality |

*Dietary factors included high consumption of red meat (including beef, lamb, and pork), low consumption of fruits, vegetables, legumes, nuts and seeds, fish, and being underweight, overweight, and obese.[131] †The Global Burden of Disease estimates[132] are based on an optimal diet similar to the reference diet. Dietary factors included fruits, vegetables, legumes, whole grains, nuts and seeds, milk, red meat, processed red meat, sugar-sweetened beverages, fibre, calcium, marine n-fatty acids, polyunsaturated fat, trans fatty acids, sodium. ‡The Alternative Healthy Eating Index-2010[133,134] used in the analysis included vegetables (potatoes not included), fruits, whole grains, sugar-sweetened beverages and fruit juices, nuts and legumes, red meat, trans fatty acids, marine n-3 fatty acids, polyunsaturated fat, and sodium (alcohol not included).

*Table 3:* **Estimated avoided premature deaths among adults by global adoption of reference diet**

### Analyses of total diets: nutrient adequacy and mortality

We quantified the healthiness of the reference diet in two ways: assessment of nutrient adequacy and prediction of mortality rates. To assess nutrient adequacy, we first analysed the nutrient composition of this diet using data primarily from the USA (appendix p 13). We also paired data on country-specific food composition and diet (figure 1) to evaluate the effect of changing to the reference diet on nutrient adequacy. In this analysis, changing to the reference diet improves intakes of most nutrients. Consumption of healthy fats (mono and polyunsaturated fatty acids) increases, whereas unhealthy fats (saturated fatty acids) decreases. The adequacy of most micronutrients increases, including several essentials ones, such as iron, zinc, folate, and vitamin A, as well as calcium intake in low-income countries. The only exception is vitamin B12 that is low in plant-based diets. Supplementation or fortification with vitamin B12 (and possibly with riboflavin) might be necessary in some circumstances.[131]

We analysed potential effects of dietary change on diet-related disease mortality using three different approaches (table 3). The first used a global comparative risk assessment framework with agricultural production and consumption statistics.[131] The risk factors included high consumption of red meat (including beef, lamb, and pork), low consumption of fruits, vegetables, legumes, nuts, and fish, and being underweight, overweight, or obese. The disease endpoints included coronary heart disease, stroke, type-2 diabetes, site-specific cancers, and an aggregate of other diseases. Relative risk factors that connect changes in dietary risks to changes in disease mortality in a dose-response manner were adopted from meta-analyses of prospective cohort studies[42,43,66,75,77,94] (appendix pp 12–13). We estimated that adopting the reference diet could avoid about 11·1 million deaths per year in 2030 and reduce premature mortality by 19%.[131]

Using a conceptually similar approach but different assumptions and data sources based on dietary surveys and food expenditure data, the Global Burden of Disease Collaborators estimated that universal adoption of a diet similar to the reference diet would prevent 10·9 million deaths per year or 22·4% of adult deaths (table 3).[132] Reduced intakes of sodium and increased intakes of whole grains, nuts, vegetables, and fruits, and low sodium intake contributed most to reduced mortality.

The third approach scored the reference diet and other diets using the Alternative Healthy Eating Index 2010,[133,134] which has predicted low mortality and disease risks in many populations.[135,136] Low scores are given for high consumption of trans fat and sugar-sweetened beverages and high scores for high consumption of polyunsaturated fat in addition to variables included in the other analyses. Sex-specific relative risks relating increments in index scores to total and disease-specific mortality rates were estimated with two large cohorts with many repeated assessments of diet (appendix pp 14–15). By applying these relative risks to dietary data and disease rates for 190 countries, we estimated that adoption of the reference diet could prevent about 11 600 000 deaths per year or 23·6% of total deaths among adults. Although methods, assumptions, and input data varied across these three approaches, they all show major health benefits of shifting global food consumption toward patterns consistent with the reference diet.

## Section 2: Sustainable food production

### Earth system perspective on sustainable food production

The need to develop and use sustainable food production practices that safeguard Earth system processes, on which food production and human wellbeing depend, has become widely recognised. Farming and fishing practices are being developed that use ecosystem services such as pest control, pollination, water regulation, and nutrient cycling to achieve productivity and resilience in agricultural landscapes, while reducing harmful environmental effects.[137] These practices include many approaches such as conservation agriculture, sustainable and ecological intensification, agroecological and diversified farming systems, precision agriculture, and organic farming.[138–140] Most of these practices focus on sustainability at the farm scale, including improvement of soil carbon concentrations, reduction of nutrient leakage from fields, and enhanced efficiency of water use by crops. Many practices also take a landscape or watershed perspective, or both by aiming to improve management of ecological processes across the whole landscape in which production is embedded.[137,141] Therefore, most work on defining environmentally sustainable food production has been done at field to landscape levels. This approach is important because visible effects on agriculture are primarily local and differ worldwide, with varying soils, hydroclimates, and agroecological zones. Thus, methods needed to minimise environmental effects of food production will vary between regions.

In the geological epoch, the Anthropocene,[142] pace and scale of local environmental effects have grown exponentially since the mid-1950s. Humans have become dominating drivers of change, and food production is the largest source of environmental degradation and has the greatest effect on the Earth system. Despite the aggregation of global effects caused by the food system, recognition of the need to adopt an Earth system approach to sustainable food production is increasing, which can no longer be defined only in terms of reducing environmental effects from local farming systems. Sustainable food production needs to include the role of food production in regulating the state of ecosystems, the biosphere, and the Earth system. Therefore, complex systemic interactions from local to global scales should be considered and global boundaries identified within which global food production needs to stay to safeguard biophysical processes that support a stable Earth system. This approach widens the perspective of how sustainable food production is defined at all scales. Increasing human change to global biogeochemical cycles provides an example. At the field scale, sustainable food production can be, and generally is, defined from a nutrient perspective (nitrogen and phosphorus application) as a system with no nutrient leakage into local groundwater and rivers. However, nitrogen and phosphorus form part of the agricultural harvest and are transported to cities or markets often far from where they were applied, causing direct nutrient pollution as food waste or untreated excreta, or partial downstream pollution after passing through municipal sewage treatment. A large proportion of nitrogen and phosphorus contributes to nutrient loading in aquatic systems, causing eutrophication of freshwater systems or coastal zones, often far from where it was originally applied as fertiliser. This process affects ecosystem resilience, carbon sequestration, and climate forcing. With increasing human extraction and loading of nitrogen and phosphorus into the biosphere, cumulatively interfering with global cycles of nitrogen and phosphorus in the Anthropocene, an Earth system perspective on nitrogen and phosphorus is necessary. Therefore, not only do environmental effects of nitrogen and phosphorus in farmers' fields need to be reduced but also the total amount of reactive nitrogen and phosphorus being added globally from the atmosphere and mines to the biosphere.

Increasing evidence shows that food production is the largest cause of global environmental change, and a transition to sustainable food production is necessary for global sustainable development. A universal definition of sustainable food production should use a system-wide assessment of environmental effects of a comprehensive set of parameters at various scales. Greenhouse-gas emissions, land and water use, nitrogen and phosphorus application, biodiversity loss, and chemical pollution from herbicides and pesticides are increasingly assessed and used in definitions of sustainable food production.[143–145] Using a uniform set of parameters when defining sustainable food production also enables consistency in meeting sustainability criteria at local and global scales. A framework that meets these two criteria—integration of a comprehensive set of system-wide environmental parameters and scale relevance from field to planet—is the planetary boundaries framework.[2,29,146] Planetary boundaries identify and define the biophysical safe operating space for environmental systems and processes that contribute to the stability and resilience of the Earth system.

We have chosen to use the planetary boundaries framework as a guide to define scientific targets for sustainable food production. The planetary boundaries framework is also useful because the six systems and processes quantified by this Commission are found within this framework; we are setting global targets and this framework relates to Earth system processes at planetary scales; and this framework has already provided various countries and sectors with a practical method of considering multiple anthropogenic, global, and environmental pressures. However, the framework does not cover interactions between various Earth system processes, although it was devised with recognition of such dynamics.

Earth system science and social-ecological resilience research show that system components and processes exist that regulate the behaviour of the Earth system and are key for global sustainability (appendix pp 15–16).[147–149] This Commission focuses on these converging strands of research to identify six systems and processes that are the main environmental systems and processes affected by food production: climate change, biodiversity loss, land-system change, freshwater use, and nitrogen and phosphorus flows.[2,150] Scientific evidence of their behaviour in the Earth system enables us to provide quantified scientific targets. These processes and systems are being increasingly recognised as necessary parameters for a system-wide definition of sustainable food production. For each of these systems and processes, we focus on the available science to propose boundaries that sustainable global food production should stay within to decrease the risk of irreversible and potentially catastrophic shifts in the Earth system. These boundaries conceptually define the upper limit of environmental effects for food production at the global scale.[2,148]

**Uncertainty in estimates of sustainable food production**

The definition of sustainable food production requires setting planetary boundaries for effects of food production on the climate system, land systems, freshwater, biodiversity, and nutrient cycles of nitrogen and phosphorus. We present underlying scientific rationale, literature sources, and assumptions behind each of the boundaries for our definition of sustainable food production. However, boundary limits for each process demarcating the shift to irreversible and deleterious changes in the Earth system are difficult to set with precision because of scientific uncertainty, natural variability, and interdependencies of Earth system processes. We use uncertainty ranges, on the basis of scientific literature and our judgment of the level of confidence, to reflect uncertainty that exists in setting global boundaries for sustainable food production (table 2).

## Climate change

*Overview*

Anthropogenic emissions of greenhouse gases cause climate change, which leads to disruptions in the Earth system, such as sea-level rise and increasing frequency of extreme weather events.[151] Systems of food production release greenhouse gases (eg, carbon dioxide, methane, and nitrous oxide) into the atmosphere directly and drive land use change that releases additional carbon dioxide when forests are cleared, wetlands drained, and soils are tilled. Food production is a prime source of methane, and nitrous oxide, which have 56 times and 280 times the global warming potential (over 20 years) of carbon dioxide, respectively.[151] Methane is produced during digestion in ruminant livestock, such as cows and sheep, or during anaerobic decomposition of organic material in flooded rice paddies. Nitrous oxide mainly arises from soil microbes in croplands and pastures and is affected by soil fertility management, such as fertiliser application. Carbon dioxide is released by agricultural land from tillage of soils and during burning to clear land of plants, soil, organic matter, and agricultural residues, and from burning fossil fuels by farm machinery, for production of fertilisers, and in transport of agricultural products. Carbon dioxide is also released when converting natural ecosystems, especially forests, to agriculture.

Biological processes that produce emissions are intrinsic to crop and livestock production and some greenhouse gases will always be generated by biological processes associated with agriculture. Therefore, although ambitious targets for reducing emissions of anthropogenic greenhouse gases should be set, eliminating all greenhouse-gas emissions (ie, methane and nitrous oxide) related to food production is not feasible. We propose a boundary for greenhouse-gas emissions from food production that is necessary and difficult to set any lower, at least before 2050, if healthy diets for the global population and targets of the Paris Agreement are to be achieved.

*A global carbon budget*

The Paris Agreement frames political and scientific consensus to keep the increase of global mean temperature by 2100 to less than 2°C, and closer to 1·5°C, relative to 1861–80 temperatures. To stay within this boundary, a maximum amount of greenhouse gases can be emitted (ie, carbon budget). This translates to a remaining budget of total global emissions from 2011 onwards of approximately 800 Gt for carbon dioxide alone, or 1000 Gt of carbon dioxide equivalent for carbon dioxide, methane, and nitrous oxide combined.[151]

Most scenarios underlying the Intergovernmental Panel on Climate Change Representative Concentration Pathway (RCP) 2.6 involve overshooting the carbon budget initially and then compensating, particularly from 2040 onwards, via large removals of carbon dioxide from the atmosphere.[152] Various negative emission technologies and actions could remove this carbon dioxide, with the most commonly promoted approaches being carbon capture and storage, and bioenergy with carbon capture and storage. However, bioenergy with carbon capture and storage might compete with land use for food production and thus have major implications for food security (appendix p 16–17).

Figure 2 summarises data[28] on probable requirements, in terms of projections of global greenhouse-gas emissions, to reach the Paris climate target. For a 66% probability of maintaining less than 2°C global warming, global carbon dioxide emissions from fossil fuel burning and industrial processes should peak no later than 2020 and reach about 5 Gt of carbon dioxide equivalent per year by 2050. Land use, land-use change, and forestry (LULUCF) emissions, dominated by emissions from agricultural expansion and land use, will have to transition by 2050 from a net global source (about 5 Gt of carbon dioxide equivalent per year) to a net carbon sink (–10 Gt of carbon dioxide equivalent per year) by 2100. The method of food production is essential to whether the Paris Agreement target of less than 2°C is attainable. Non-carbon dioxide emissions will need to be reduced, particularly methane and nitrous oxide, in food production and the world's food production systems transformed from net carbon sources to net carbon sinks. Achieving the Paris Agreement will also require rapid global decarbonisation of the energy system, including that used by agriculture.

*Status of emissions associated with food production*

Estimates of agriculture's net greenhouse-gas emissions vary widely depending on which subcategories are included: emissions of non-carbon dioxide gases (methane and nitrous oxide) from agricultural production are estimated to be 5·0–5·8 Gt of carbon dioxide-equivalent per year;[153] carbon dioxide emissions from conversion of natural ecosystems, especially forests, to croplands and pastures is estimated to be 2·2–6·6 Gt of carbon dioxide equivalent per year,[154] and a small amount from biomass burning of about 0·3 Gt of carbon dioxide equivalent per year;[153] and carbon dioxide emissions from energy use in agricultural machinery are estimated at 1·0 Gt of carbon dioxide equivalent per year.[155] The total estimate of all greenhouse-gas emissions from food production is 8·5–13·7 Gt of carbon dioxide equivalent per year. Total emissions from food production have been stable since 1990, growing less than 1% per year, because increases in production have been offset by decreasing emissions intensity per unit of product.[153,155]

Determining the maximum allowed share of the remaining global carbon budget that might come from food production is complex, and any scientific target, if all emission sources are considered equal, will depend on viability and costs of emission reductions in other sectors. Therefore, we attempt to estimate the maximum allowable carbon budget for food production, which is based on an estimate of the minimum amount of greenhouse-gas emissions from biological activities associated with agriculture that we consider are difficult, if not impossible, to avoid over the next 30 years. We assess the unavoidable share of greenhouse-gas emissions from food production until 2050. This excludes all carbon dioxide emissions from burning of fossil fuels and from land use change, which we assume have been reduced to zero, and consider only methane and nitrous oxide associated with biological processes in crop and livestock production.

We propose that global greenhouse-gas emissions of methane and nitrous oxide from food production be kept at or less than 5 Gt of carbon dioxide equivalent per year in 2050. This scientific target represents nearly half of the allowable global emissions from all sources in 2050, consistent with the RCP2.6 and a 2°C temperature rise. This proportion of food production's share of global greenhouse-gas emissions by 2050 is thus larger than today's share, which accounts for about a quarter of total global greenhouse-gas emissions.

This scientific target is based on combined projections of methane and nitrous oxide emissions of 4·7 Gt of carbon dioxide equivalent per year from food production, which is derived from three integrated assessment models:[156] IMAGE 4.28, MESSAGE 4.41, and GCAM 5.30 under RCP2.6 reported by Wollenberg and colleagues[156] and corroborated for IMAGE by van Vuuren and colleagues.[157] Integrated assessment models generate these results by running submodels of climate systems, socioeconomics, energy use, land use, and other subsystems, to allocate

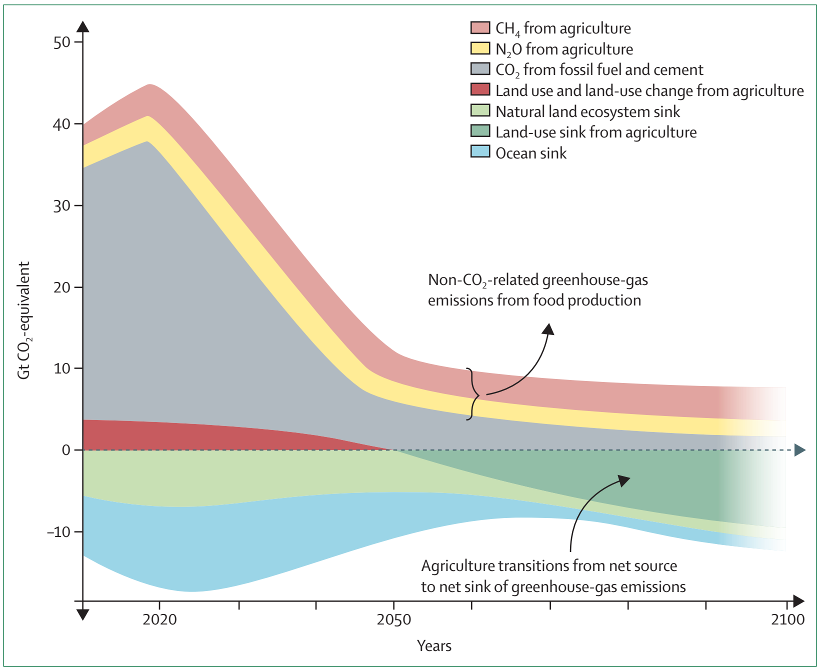


***Figure 2:*** **Projections of global emissions to keep global warming to well below 2°C, aiming for 1·5°C**
Data are from Intergovernmental Panel on Climate Change fifth assessment report (RCP2.6 data for nitrous oxide and methane) and Rockström and colleagues[28] (for fossil-fuel emissions, land use, land-use change, and forestry, and biosphere carbon sinks).

emission reductions most cost-effectively across sectors and greenhouse gases. RCP2.6 projects that methane emissions from food production will decrease gradually throughout the 21st century, whereas nitrous oxide emissions are expected to plateau after 2050.[157,158] In addition to methane and nitrous oxide emissions, biomass burning on agricultural land, which releases carbon dioxide, is expected to contribute an additional 0·7 Gt of carbon dioxide in 2050 under RCP2.6.[157,158] Combining these three gases gives a total of 5·4 Gt of carbon dioxide equivalent per year. Because of the uncertainties associated with emission estimates, we set the boundary as 5 Gt of carbon dioxide equivalent per year with an uncertainty range of 4·7–5·4.

The scientific target for greenhouse-gas emissions from food production will be achieved on the basis of two fundamental assumptions. First, zero carbon dioxide emissions will be associated with land clearance for food production. If land-use change (eg, deforestation and other land conversion) for food production is reduced to zero, then no greenhouse gases will be released from this source. This goal is ambitious and goes beyond the RCP2·6 for carbon dioxide emissions associated with land-use change. Second, zero net emissions will come from energy use in food supply chains. Greenhouse-gas emissions from use of fossil fuels in food production are ascribed to the energy sector, not the agriculture sector, in the IPCC and other emissions-accounting frameworks. Analyses also propose a global transition to clean energy by 2050, bringing emissions from energy use in all sectors to zero.[28]

## Freshwater use

*Overview*

Food production is the world's largest water-consuming sector. 84% of cropped land uses freshwater from rain, and the remaining 16% uses irrigation (ie, water in freshwater lakes, rivers and aquifers).[159] 70% of all global water withdrawals are used for irrigation. This share of water withdrawals for food production varies between regions, from 21% in Europe to 82% in Africa. Water consumption for food production has more than doubled between 1961 and 2000.[160]

Water is the bloodstream of the biosphere.[161] Water supports all biomass growth and determines the extent and distribution of biomes and ecosystems. Water drives nutrient cycles, including flushing and leaching of nutrients and pollutants (heavy metals and plastics). The hydrological cycle is associated with climate systems, including moisture feedback dynamics determining regional precipitation.[162] However, we focus on the quantity of water needed to maintain minimum levels of environmental water flow in watersheds and river basins, and thus to sustain ecosystem health and benefits that society receives from these systems.

Environmental flows are the "quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems".[163] These flows are the result of upstream freshwater partitioning of rainfall into evaporation or runoff and are affected by withdrawals of water for irrigation or other uses. For example, irrigated agriculture upstream requires large withdrawals of water, which will decrease environmental water flow in rivers. This reduction in flow can affect downstream ecological functions that are important for society, such as drinking water supplies, fisheries, nutrient retention, and pollution control.

To understand the effects of water withdrawals on environmental flows, the difference between consumptive water use and non-consumptive water use should be recognised. Consumptive water use refers to water that is removed from a watershed by evapotranspiration (loss of water from direct evaporation or plant transpiration), thereby directly reducing environmental water flows. Non-consumptive water use refers to water use that flows back to rivers and aquifers after use. Most irrigated water is for consumptive water use thus making it unavailable for other uses in the watershed. Only a small proportion returns directly to watersheds as surface or groundwater runoff. Up to 75–84% of global consumptive water use can be attributed to agriculture.[160,164]

Environmental flow requirements (EFRs) are the minimum water volume, timing, and quality needed to maintain environmental function and downstream benefits. The EFR defines allowable upstream withdrawals and consumption that sets basin-scale boundaries for water use that ensures adequate environmental flows in watersheds. Hydrological dynamics (ie, low-flow and high-flow values) and the ecological context of individual watersheds and river basins affect EFR values.[165] Therefore, water is best analysed regionally at the basin level.

The original planetary boundary for water was proposed as 4000 km³/year on the basis of a global analysis that did not account for distinct hydro-ecological contexts and EFRs of individual river basins.[146] This boundary did not include water use by crops in rain-fed agriculture nor water loss through evaporation from dams.[166] Some people have argued that this boundary is too high and should be lower.[167] Gerten and colleagues[168] refined the water boundary with a global analysis at the scale of river basin EFRs, quantifying available freshwater withdrawals if EFR requirements were to be respected. Gerten and colleagues offer a conservative global freshwater planetary boundary of 2800 km³/year for all human use including food production.[168] Consumptive water use by all human activities has been estimated to be 1800–2100 km³/year, of which food production uses 1400–1800 km³/year.[160,164]

For setting a global scientific target for consumptive water use from food production, we have chosen to adopt the conservative planetary boundary of 2800 km³ year.[168] Agriculture's share of global consumptive water use is 75–84%.[169] If this quantity is maintained, food production's share of the planetary boundary for freshwater would be 2100–2352 km³/year. Because food production is fundamental to human wellbeing and closing yield gaps in many parts of the world is essential to feeding the global population, we suggest that the agriculture sector should be allowed a larger future allocation of the overall planetary boundary. Setting the agricultural share of the 2800 km³/year planetary boundary to 90% by 2050, rather than 75–84%, yields a global water boundary for food production of about 2500 km³/year. However, because of uncertainty in these estimates, we have used Gerten and colleagues'[168] uncertainty range of 1100–4500 km³/year. Applying a 90% allocation for food production gives an uncertainty range rounded to 1000–4000 km³/year.

We believe increasing food production's share of global consumptive water use to 90% is feasible because many technological solutions can limit consumptive water use in industry and domestic sectors. Wada and colleagues[160] found that in high-income countries with advanced technologies, 20% of consumptive water losses in industry are due to water withdrawals, whereas in middle-income countries and low-income countries, water withdrawals causes 35% and 60% of losses, respectively. This finding suggests that substantial reductions are possible through improved use of existing technologies. In food production, consumptive water use is unavoidable since plants transpire to grow and water evaporates from soil. Management practices can reduce evaporative losses through improved irrigation technologies; however, some losses will remain unavoidable because of plant growth.

*Regional considerations*

The global estimate of consumptive water use masks substantial regional variations, with some regions well within the boundary and others facing severe water shortages. Severe water shortages are particularly common in arid regions that are chronically short of water and where basin scale EFRs are overtaken by irrigation (appendix p 17). Water use is an issue at the regional and river-basin level and local and regional boundaries need to be set depending on their specific EFRs. The global boundary we propose is an aggregate of water use by region. In addition to using EFRs, Gleick and Palaniappan[170] propose using peak non-renewable water and peak ecological water, whereby total costs of ecological disruptions from water use exceed the total value provided by humans, as indicators of freshwater withdrawal and use.

Assuming an ideal trade scenario, integrity of water basins could be maintained through trade. Basins with surplus water could deliver water to basins in deficit by trading water-intensive food products. This would require unimpeded food trade and all countries to possess sufficient foreign currency to purchase food. However, in the current political climate, high pressure exists towards enhancing food sovereignty (or self-reliance) through local food production. This pressure places large demands on water resources, especially in arid and semi-arid developing countries. Low-income nations that are unable to trade because of political or economic reasons are most at risk.

**Nitrogen and phosphorus flows**

*Overview*

Nitrogen and phosphorus are nutrient elements, vital to the structure and metabolism of living organisms on land and in oceans. Nitrogen and phosphorus are crucial for plant growth, but their natural availability limits plant growth in most terrestrial ecosystems. Supply of nitrogen and phosphorus fertilisers to croplands is essential for maximising crop yields and will continue to be necessary for feeding a growing global population.[171]

Production, application, and trade of fertilisers disrupts global nitrogen and phosphorus cycles. Excessive application of nitrogen and phosphorus in food production has substantial consequences, notably in runoff into streams and rivers, driving eutrophication of freshwater and marine ecosystems and subsequent development of hypoxic (oxygen-free) conditions causing fish dieback and other environmental harm.[17] Although mostly driven by excessive application of fertiliser in food production, human sewage is also an important source. Atmospheric nitrogen deposition, usually carried by rain, snow, or fog to the Earth's surface, is a third important contaminant source, particularly in countries with high nitrogen oxides (ie, nitrogen oxide and nitrogen dioxide) and ammonia emissions.[172]

In addition to eutrophication of aquatic ecosystems, nitrogen application in agriculture can have several other environmental and health effects, including eutrophication of terrestrial ecosystems, reducing their biodiversity and altering ecosystem functions;[173,174] acidification of water and soils by ammonia emissions;[175] nitrous oxide emissions, which is a potent greenhouse gas;[176] groundwater contamination by nitrates, which negatively affects human health;[177] and creation by ammonia of fine atmospheric particulate matter and its harm to human health.[178] Agricultural nitrogen also drives nitrogen oxides emissions, which are a major source of particulate and ozone pollution[179] and contribute to reduced crop yields.[180]

Nitrogen fertiliser is created using the Haber-Bosch industrial process to convert plentiful non-reactive nitrogen gas to ammonia. This process is highly energy intensive and associated with high levels of greenhouse-gas emissions. Conversely, phosphorus fertiliser is a non-renewable resource that is mined from a finite number of phosphate rock deposits. At existing and projected rates of exploitation, these deposits are estimated to run out within 50–100 years.[181]

*Nitrogen and phosphorus for people and planet*

A major challenge for humanity is to harmonise the maximum allowed nitrogen and phosphorus loading into the biosphere to maintain a stable Earth system, with the necessary amounts of nitrogen and phosphorus required to feed the global population.[182] Estimates of human needs show that feeding about 10 billion people by 2050 on existing cropland will require higher annual global applications of nitrogen and phosphorus fertilisers[183] that exceed the planetary boundaries for nitrogen (62–82 Tg per year) and phosphorus (6·2–11·2 Tg per year). However, this Earth system approach increases opportunities to feed humanity if practices are adopted in which more food is produced per unit of nitrogen or phosphorus input, loss of nutrients is reduced to a minimum, and nutrients are recycled, not only on farmers' fields, but also at system level (eg, in the rural–urban interface). Experience shows that ample opportunities exist to reduce environmental effects of food production by eliminating nutrient overuse and run-off into aquatic systems, while still allowing increased food production.[184]

Closing nutrient loops and using nitrogen and phosphorus efficiently is one opportunity for increasing food production without releasing more reactive nitrogen and phosphorus into the biosphere. This strategy includes applying the right type and quantity of fertiliser, at the right time, and in the right place. The strategy also involves efforts to recover nutrients (ie, recycling) in usable forms from places in the food system where they concentrate, such as sewage treatment plants, food processing plants, compost operations, and livestock production facilities. Adopting a closed loop system in global food production recycles nitrogen and phosphorus within food systems, keeping it out of the biosphere, and decreasing environmental effects. Improved nutrient use and re-use efficiency can permit increased global application of nitrogen and phosphorus to close yield gaps (ie, the difference between attainable and actual yields) while reducing total global need for synthesis of new nitrogen and phosphorus fertilisers.

Another opportunity arises from redistribution of nitrogen and phosphorus use to close yield gaps. On a global scale, application of nitrogen and phosphorus fertiliser is highly unevenly distributed, ranging from nitrogen and phosphorus inputs insufficient to close yield gaps to excessive surplus application in many developed and rapidly growing economies.[185] Many developed nations apply nitrogen in excess, with rates of nitrogen application exceeding those needed to obtain yields. By contrast, many developing countries have yields that are only a half to a quarter of those that could be obtained with appropriately increased and well-timed applications of fertiliser.[184,185]

Nitrogen fluxes (ie, net movement of nitrogen) to air and water react directly to increases in nitrogen input because nitrogen does not accumulate in soils. Therefore, increases in nitrogen added to croplands increases expected nitrogen losses due to leaching and runoff into aquatic systems, volatilisation to air, and crop removal, which accounts for most nitrogen that leaves the soil system. This direct link between inputs and losses formed the basis of the anthropogenic nitrogen input calculation by De Vries and colleagues,[183] which is the amount of nitrogen that can be applied (from fixation by legumes and fertiliser) globally for food production without causing eutrophication. The essential input of nitrogen (ie, nitrogen application) is a fraction of the existing global nitrogen input, which currently exceeds planetary boundaries.

The nitrogen boundary for global food production is derived by muliplying estimated global application and biological fixation with mean fractions varying between 0·50 and 0·67 of global nitrogen application. These mean fractions relate to the percentage of reductions in global nitrogen application necessary to keep nitrogen concentrations in runoff within safe limits of 1–2·5 mg of nitrogen per L.[183] Total global application of nitrogen is estimated to be about 130 Tg per year.[183] Multiplying 130 Tg of nitrogen per year by 0·50 and 0·67 gives 65–87 Tg of nitrogen per year, with the proposed global application boundary of nitrogen for food production set at 90 Tg of nitrogen per year and an uncertainty range of 65–90. This application boundary is slightly higher than that proposed by Steffen and colleagues[2] who used a total global nitrogen application of 121·5 Tg per year, which might be based on an underestimation of fertiliser use.

The proposed nitrogen boundary from food production might still be an underestimate because it is based on global patterns of nitrogen use, which includes overuse in some areas and underuse in others. In deficit areas, additional nitrogen input to increase crop yield is possible without negatively affecting the environment. Additionally, the nitrogen boundary does not consider efficiency gains through closing nitrogen loops. If global redistribution of nitrogen and closing nitrogen loops are considered, a higher global use of nitrogen than 90 Tg per year might be possible without exceeding the boundary for food production. We therefore include an upper uncertainty range of 90–130 Tg of nitrogen per year that considers an increase in use of nitrogen fertiliser[184] if nitrogen is globally redistributed and nitrogen loops are closed. This upper value of 130 Tg of nitrogen per year is a human needs estimate for nitrogen that might be required to feed a global population of about 10 billion people.

The planetary boundary of 6·2 Tg of phosphorus per year (uncertainty range 6·2–11·2), originally proposed by Carpenter and Bennett[186] and adopted by Steffen and colleagues[2] was a regional level, short-term boundary to avert widespread eutrophication in regional watersheds. This boundary was applied primarily to global croplands because most phosphorus addition to watersheds is from fertiliser use. This boundary is based on the total global flow of phosphorus in erodible soil to freshwater systems minus weathering rates. However, this approach assumes that soil erosion is the main source of phosphorus to freshwater systems. Phosphorus that is removed from fields by crops, consumed by animals and humans, and excreted as manure and human waste and ending up as phosphorus inputs to freshwater systems are excluded. This exclusion might drive overestimation of the long-term global phosphorus boundary of sustained flow of 11 Tg of phosphorus per year (uncertainty range 11–100) from freshwater systems into the ocean.

De Vries and colleagues[183] developed a global phosphorus-flow model for food production that considers some criticisms of the original approach used by Carpenter and Bennett[186] but did not consider other fluxes, such as weathering rates. In this model, the external, acceptable, global input of phosphorus from food production to the biosphere is determined by long-term (thousands of years) acceptable accumulation of phosphorus in soil and sediments and inputs to surface water (oceans) from runoff and leaching that increases phosphorus concentration to a threshold for eutrophication. Phosphorus uptake and excretion by humans to freshwater systems (stored in sediments) and recycling of human waste to soils (stored in soils) affects this boundary. This boundary assumes full phosphorus recycling from animal manure. Using this approach and assuming no recycling of human waste gives a long-term global input of phosphorus from food production of about 6–12 Tg of phosphorus per year. This new estimate is similar to the Carpenter and Bennett[186] input range. We therefore propose the global long-term boundary of phosphorus application from food production to be 8 Tg of phosphorus per year (uncertainty range 6–12). This phosphorus boundary might be underestimated because the effect of improving efficiency of phosphorus use through closing phosphorus loops by recycling and reducing point source loads is not considered. This boundary also does not consider global redistribution of phosphorus use from regions that overapply phosphorus fertiliser to those that underapply. This redistribution is important because, unlike nitrogen, phosphorus is adsorbed onto soil and can accumulate and be stored in stocks of soil phosphorus. Increasing organic matter and stored carbon in soils increases the capacity of soils to store phosphorus. Phosphorus leaching and runoff to surface waters occurs when phosphorus stocks in soils are saturated and phosphorus input from fertiliser is greater than the quantity of phosphorus removed during cultivation and harvest. When soils are deficient in phosphorus (ie, stocks are not saturated), additional inputs of phosphorus are possible and will increase yields with minimal environmental harm. Together, these considerations effectively increase the phosphorus boundary.

Global stocks of phosphorus are deficient in some areas and saturated in others. To increase crop yields, global phosphorus stocks should be saturated globally, and phosphorus application should maintain saturation by replacing phosphorus that is removed during cultivation and harvest. This process would close yield gaps, which is necessary for feeding about 10 billion people by 2050. We estimate that this target can be met through short-term time-bound (over a few years) global phosphorus application of 16 Tg per year, targeting soils with phosphorus deficit. Therefore, we propose an upper input of 8–16 Tg of phosphorus per year, while maintaining a boundary of 8 Tg per year, which can be achieved by recycling 50% of human waste and reapplying recycled phosphorus to croplands.[187] This approach will increase in importance as the global population increases by more than 2 billion people by 2050.

## Biodiversity loss

### *Overview*

The diversity and richness of all living organisms on land and in water is necessary for the stability of ecosystems,[188,189] and productivity and resilience of food production systems. This functional value of biodiversity is often poorly understood and hugely undervalued.[190,191] Biodiversity enhances ecosystem services necessary for human wellbeing, including food production, pollination, pest control, heat regulation, carbon sinks, and moisture feedback for rainfall. Nutritional quality, protective attributes, and flavours of most plant foods is a function of evolutionary interactions between species (panel 4).[192]

We have entered the sixth mass species extinction on Earth, losing species at a rate 100–1000 times greater than Holocene rates.[193–195] This loss is measured through rates of species extinction,[194,195] local changes in community composition, declines in population abundance,[194] and reduced biodiversity intactness.[150] This species extinction is an increasing threat to the Earth system[188,189] and global food security and has the potential to fundamentally undermine our ability to sustainably feed the global population by 2050.

### *Food production as a driver of biodiversity loss*

Multiple human actions contribute to biodiversity loss. Terrestrial and aquatic habitat loss, habitat fragmentation, climate change, chemical pollution, invasive species, and unsustainable harvest of wild species have been identified as primary drivers.[190,196] However, habitat loss and fragmentation, particularly through human appropriation of land for food production, is the greatest driver of biodiversity loss.[190,197] Based on the International Union for Conservation of Nature classification of bird and mammal extinction risks, 80% of extinction threats to mammal and bird species are due to agriculture (appendix p 17).

Current extinction rates[198] and population declines[194] are higher than those in the Holocene of about one extinction per million species per year. The number of species that can become extinct while maintaining the ability to feed humanity remains unknown, but each additional species lost represents a fundamental reduction in resilience and capacity to respond to environmental change.[199] A precursor to extinction is the reduction of species' population sizes and local extinctions. Insect biomass has reduced by 75%[200] in 30 years and farmland birds by 30% in 15 years; this decline has occurred long before global

**Panel 4: Agricultural biodiversity**

Agricultural biodiversity, or agrobiodiversity, is important to human wellbeing and is directly associated with dietary health. Agrobiodiversity, often referred to as crop diversity, includes cultivated and uncultivated species that comprise foods we eat or support food production. Cultivated agrobiodiversity encompasses species intentionally planted or reared by farmers. This diversity originates from tens of thousands of years of farmer selection producing various edible species suited to many social and environmental contexts.

Non-edible agricultural biodiversity includes a myriad of species, from soil microbiomes, to insects, birds, and mammals that pollinate crops, regulate pests, absorb excess nutrients from fields, and store carbon in soils. Benefits provided by this biodiversity are called agroecosystem services. Production practices such as agroforestry, riparian buffers, wild field margins, or conservation tillage help to conserve biodiversity in fields, and these services are managed and secured[A20] for food production.

Because plants are non-mobile, they have evolved numerous chemical adaptations for protection against predators and diseases—sweet rewards to animals who disperse their seeds (eg, fruits and berries) or providing their offspring with large energy stores for germination and growth (eg, seeds and nuts). These adaptions are the source of the diverse nutritional values of plant foods. Consuming a diversity of fresh fruits and vegetables, whole grains, seeds, and nuts is an important part of a healthy diet, benefiting from this evolutionary history and resultant diversity.[A21]

However, of more than 14 000 edible plant species, only 150–200 are used by humans with only three (rice, maize, and wheat) contributing 60% of the calories consumed by humans.[A22, A23] Many underused plant species have excellent nutritional profiles, as well as traits of interest for adapting food production to climate change (ie, quinoa, millet, sorghum, or teff for grains, or zapote, chaya, or chenapodes for fruits and legumes). These qualities are especially important considering the increasing risk that climate change will pose on crop yields and the nutritional content of foods. However, food system simplification drives loss of these plant species and varieties, reducing options that support healthy diets from sustainable food systems.

References cited in this panel can be found in the appendix (p 27).

extinctions but has severely affected biodiversity's capacity to support food production, gene flow, and other ecosystem services.

A background extinction rate of one extinction per million species per year across many taxa has been proposed as a benchmark against which to assess effects of human actions.[195] A high degree of uncertainty exists about the rate of extinctions that the Earth system can tolerate, which is distinct from, and less conservative than, intrinsic biodiversity value benchmarks that argue for zero species loss. This uncertainty therefore justifies high uncertainty and our proposed scientific target of less than ten extinctions per million species per year, which is within one order of magnitude greater than the background extinction rate and the same target suggested by Steffen and colleagues.[2] However, because the rate or types of biodiversity loss that could trigger irreversible changes to the Earth system are unknown, the boundary from food production should be set at a rate of loss no greater than the historical background rate. Therefore, we suggest an uncertainty of 1–80 extinctions per million species per year, with the lower value (ie, 1) being equal to the background extinction rate and the upper value (ie, 80) being agriculture's share of effect on species decline—ie, 80% of the upper value of the uncertainty range (100 extinctions per million species per year) proposed by Steffen and colleagues.[2]

Although extinction per million species per year is a logical metric for measuring biodiversity loss, several caveats are important to recognise. First, extinction per million species per year is typically measured on geological timescales rather than on ecological time scales of global environmental conventions, including the Convention on Biological Diversity. However, early indications of global extinctions are becoming observable in ecological timescales and is cause for concern requiring urgent action. Second, regional reductions in species populations[194] and local extinctions are a precursor to global extinction and better measured with a regional metric, such as biodiversity intactness index, than a logical metric. Third, not all species have the same measurable effect on Earth system processes, and thus species loss might not capture the extent to which an individual species lost affects global processes.[201] Despite these limitations, models based on well documented species area relationships have been used to extrapolate the extent to which anticipated land conversion could contribute to species loss.[202,203] Therefore, we maintain extinction per million species per year as the appropriate metric for measuring global biodiversity loss from food production.

## Land-system change

### *Overview*

Globally, the net area for food production has remained constant since the mid-20th century. However, this trend masks the real picture because substantial reductions in agricultural land have occurred in temperate regions of Europe, Russia, and North America, whereas substantial expansion of agricultural land has occurred in biodiversity-rich tropics. Food production is the largest driver of land use and land-use change, mainly through clearing of forests and burning of biomass. Between 2000 and 2014, Brazil lost on average 2·7 million ha/year of forest, the Democratic Republic of Congo lost 0·57 million ha/year with a 2·5 factor increase since 2011, and Indonesia lost 1·3 million ha/year, with 40% occurring in primary forest.[204] This land-system change is a major contributor to biodiversity loss and greenhouse-gas emissions and undermines other Earth system processes.

The challenge of land use is to safeguard essential terrestrial and marine biomes that regulate the state of the planet and provide ecological functions that support food production. About 51% of the global land surface can be classified as intact ecosystems with a biodiversity intactness index greater than 90.[150,205] The biodiversity intactness index provides a measure of the intactness of local communities within a region relative to their original state. However, intact ecosystems vary globally with highly intact biomes in boreal and tundra biomes.[205] Of this 51%, approximately 15% of global land area has legal protection status and can be classified as natural habitats, which are home to unique species. Many of these species are severely threatened and require large intact areas with little to no human intervention. The Convention on Biological Diversity Aichi Target 11 has set a global target to protect 17% of terrestrial and inland water areas, with a focus on legal protection of key biodiversity areas[206] and hotspots.[207]

The remaining 36% of intact ecosystems do not have legal protection status but maintain high values of biodiversity intactness.[205] The most threatened biomes are those with greatest agricultural value, including grassland, dry tropical forest, and temperate forest biomes. By contrast, biomes that have low values of biodiversity intactness for food production are well conserved and protected, notably high latitude tundra and boreal forest biomes. The combination of intact biome areas (>50%) and biodiversity intactness (>90 biodiversity intactness index) provide a set of metrics that highlight the extent to which progress should be made to protect global biodiversity (figure 3). Because biodiversity is local and non-tradable, these targets should be set at the ecoregion level thus ensuring an even distribution of conservation efforts globally.

Most of the remaining land surface is dedicated to croplands and grazing lands (ie, rangelands and pasturelands), which occupy about 40% of ice-free terrestrial landmass. Jointly, these agricultural systems are the world's largest ecosystems and, in addition to food production, they provide other important services, such as habitat for biodiversity and carbon sinks. Of this 40%, grazing lands occupy about 23% of land surface and are important for biodiversity conservation and carbon sequestration. Grazing lands might also be particularly important in restoration strategies in formerly grassland biomes or reforestation in formerly forest biomes, both of which are important carbon sequestration strategies. However, reforestation is constrained by land availability and therefore reforestation of degraded pastures and rangelands in original forest biomes offers an opportunity to remove carbon dioxide from the atmosphere while providing additional benefits of biodiversity conservation.[208] Conversion of the remaining rangelands and pasturelands should be treated with caution because the opportunity cost resulting from biodiversity loss and carbon dioxide emissions is high.

We use minimum forest cover, biodiversity intactness index, and area-based intactness for key biomes as guides for setting the scientific target for land use from food production.[2] Since agriculture is the largest driver of deforestation and land-use globally, to achieve the Paris Agreement and reduce biodiversity loss, agricultural expansion into forest areas and other natural ecosystems should be stopped. Therefore, global land use from food production should be kept at or below 13 M km² (11–15 M km²).

*Half Earth strategy*

Proposals suggest that we can halt biodiversity loss and conserve at least 80% of preindustrial species richness by protecting the remaining 50% of Earth as intact ecosystems.[205,209] Quantitative boundary estimates for land-system change and biodiversity loss proposed by this Commission can thus be translated to (globally) zero future land conversion of natural ecosystems into farmland (ie, to implement a Half Earth strategy). This strategy complies with the biome or regional boundary proposed by Steffen and colleagues[2] of maintaining a biodiversity intactness index of 90% (figure 3). Implementing a Half Earth strategy by biome would have multiple co-benefits, such as maintaining functional diversity in ecosystems, reducing greenhouse-gas emissions from agriculture, forestry, and other land use, and stimulating afforestation or reforestation efforts, which are important for helping to meet the Paris Agreement. Half Earth can be achieved through legal protection or land uses compatible with biodiversity such as sustainable harvest of native forests, indigenous areas, or low-intensity grazing systems in grassland ecosystems, or other land uses that maintain a biodiversity intactness index of less than 90.

Staying within the biodiversity boundary for food production also depends on fine-scale conservation efforts within agricultural landscapes. Most of biodiversity loss is driven by habitat fragmentation and agricultural intensification, including loss of fallows, buffer systems, and embedded conservation structures in agriculture. Integrating a minimum of 10% of ecologically conserved land at fine scales (<1 km²) into agricultural systems enables habitat connectivity, which is essential for species survival, and access to the services biodiversity provides to support food production. In addition, alteration of ecosystems due to climate change causes less biodiversity loss than does land use change. Ensuring that species can adapt to the pace of climate change requires conservation of habitat and connectivity.[210]

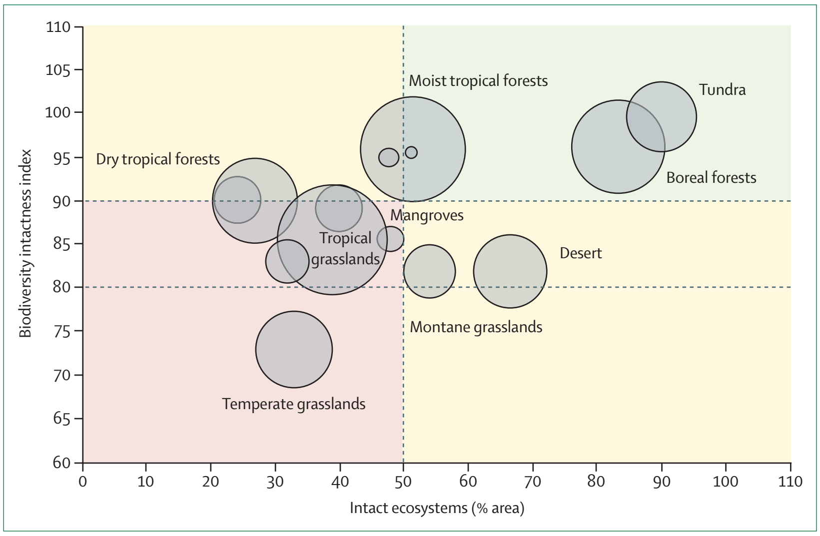


***Figure 3:*** **Association between area-based intactness of ecosystems and the species composition-based biodiversity intactness index to measure current biome status with regard to area-based and species-based conservation targets**

The size of the circles reflects the extent (ie, area) of the biome. The dashed lines represent area-based (x axis) and species-based (y axis) targets. Area-based intactness and Half Earth target (50%) was proposed by Wilson[209] and Dinerstein and colleagues.[205] The species composition-based biodiversity intactness index was proposed by Steffen and colleagues,[2] representing functional biodiversity, and analysed globally by Newbold and colleagues.[150] Four biomes (green shaded area) have a biodiversity intactness index greater than 90 and an area-based intactness of more than 50%; one biome, temperate grasslands, is below 50% area-based intactness and 90 species-based intactness index. Four biomes fall below area-based and species-based targets if the biodiversity intactness index threshold is 80%. The remaining biomes fall below one, but not both area or species composition-based targets. For descriptions of each biome see the appendix (pp 18–19).

## Scientific targets and strategic directions for sustainable food production

Table 2 provides scientific targets for the planetary boundaries for food production presented in this Commission. These global scientific targets provide an integrated definition of sustainable food production, which can be translated to science-based targets for different scales (regions and nations) and sectors. Furthermore, scientific targets for sustainable food production can be translated to strategic directions including: (1) decarbonise the food value chain from production to consumption—ie, zero fossil fuels by 2050 and maintain greenhouse-gas emissions at or less than 5 Gt of carbon dioxide equivalent per year for methane and nitrous oxide associated with food production; (2) radical improvement in efficiency of systems-scale (including rural and urban) nutrient use and recycling of nitrogen and phosphorus; (3) urgent move towards zero loss of biodiversity; (4) feed humanity on existing agricultural land—ie, transition to zero expansion of new agricultural land at the expense of natural ecosystems; (5) integrate 10% of ecological conservation into existing agricultural landscapes and regenerate and reforest degraded land; (6) adopt a Half Earth strategy for biodiversity conservation by protecting 50% of Earth as intact ecosystems; (7) reduce food loss and waste by 50% to decrease pressure on food demand; and (8) transform to sustainable intensification of food production and adopt sustainable practices for soil, water, nutrients, and chemicals thus revolutionising agriculture.

## Section 3: Achieving healthy diets from sustainable food systems

### Introduction

Devising a sustainable food system that can deliver healthy diets for a growing population presents formidable challenges (see Section 4). Finding solutions to these challenges requires understanding of the environmental effects of multiple variables. We apply a global food system modelling framework to analyse what combinations of readily implementable measures (table 4) are needed to stay within food production boundaries (table 2) while still delivering healthy diets (table 1) by 2050. The aim is to find a set of actions within scientific targets set by this Commission for human health and environmental sustainability.

### Environmental effects of foods

Methodological inconsistencies and data gaps make it difficult to distinguish and compare, with a high certainty, the precise environmental footprints of individual food products. Most existing food and diet studies assessing environmental impacts consider only greenhouse-gas emissions and recent reviews of the literature show a lack of integrated analysis and an under-representation of some of the core environmental impact dimensions of food systems. Particularly biodiversity, animal welfare, nutrient leaching, and the use of chemicals are generally missing from food footprint studies. However, results from a large and growing body of literature points towards a very likely clear hierarchy of impacts among larger food categories. For instance, Clune and colleagues[216] present greenhouse-gas emissions of different food categories from life-cycle assessment studies and show that grains, fruits, and vegetables have the lowest environmental effects per serving, and meat from ruminants the highest effects per serving. Other studies[217] have assessed the environmental effects of water use. Overall, studies concur that plant-based foods cause fewer adverse environmental effects per unit weight, per serving, per unit of energy, or per protein weight than does animal source foods across various environmental indicators (figure 4). Seafood is a particularly diverse food category and environmental effects can differ substantially between captured and farmed fish and shellfish, and within certain subgroups (eg, farmed salmon *vs* farmed freshwater fish such as carp, and farmed shrimps *vs* farmed mussels.

Environmental effects of foods can be measured with various units, including per kcal, per g protein, or per serving, depending on the nutritional contribution of each food.[4] Using a universal indicator to measure environmental effect can be misleading for some foods. For example, vegetables contain few calories per serving and thus using kcal to measure their environmental effect would indicate that some vegetables have high environmental footprints whereas, from a per serving basis, their environmental effects are low. Given this ambiguity, environmental effects are shown per serving in figure 4.

### Environmental effects of overall dietary patterns

Many studies have assessed environmental effects of various diets, with most finding decreasing effects with increased replacement of animal source foods with plant-based foods.[5,6,218–220] Vegan and vegetarian diets were associated with the greatest reductions in greenhouse-gas emissions and land use,[5,221] and vegetarian diets with the greatest reductions in water use.[219] Diets that replaced ruminants with other alternatives, such as fish, poultry, and pork, also show reduced environmental effects, but to a smaller extent than plant-based alternatives.[220] These studies show a diet including more plant-based foods than animal source foods would confer environmental benefits and improved health (Section 2). By contrast, agricultural studies[140,184,222] have investigated potential changes in technologies and management that could decrease environmental effects—eg, increasing yields of existing croplands and improving water and fertiliser management.

| | Assumptions |
|---|---|
| Dietary shift | Reference (table 1); vegetarian: meat-based protein sources replaced by a mix of plant-based proteins and fruits and vegetables (eggs and dairy consumed); vegan: all animal-based protein sources replaced by a mix of plant-based proteins and fruits and vegetables (no eggs and dairy consumed); pescatarian: meat-based protein sources replaced by a mix of seafood and fruits and vegetables (eggs and dairy consumed) |
| Improved production practice (PROD) | Standard level of ambition for improved food production practices including closing of yield gaps between attained and attainable yields to about 75%;[184,211] rebalancing nitrogen and phosphorus fertiliser application between over and under-applying regions;[184] improving water management, including increasing basin efficiency, storage capacity, and better utilisation of rainwater;[211] and implementation of agricultural mitigation options that are economic at the projected social cost of carbon in 2050,[212] including changes in irrigation, cropping and fertilisation that reduce methane and nitrous oxide emissions for rice and other crops, as well as changes in manure management, feed conversion, and feed additives that reduce enteric fermentation in livestock[213] |
| Improved production practice (PROD+) | High level of ambition for improved food production practices on top of PROD scenario, including additional increases in agricultural yields that close yield gaps to 90%;[184] a 30% increase in nitrogen use efficiency,[214] and 50% recycling rates of phosphorus;[215] phase-out of first-generation biofuels, and implementation of all available bottom-up options for mitigating food-related greenhouse-gas emissions[213] |
| Reduced food waste and loss (halve waste) | Food losses and waste reduced by half, in line with Sustainable Development Goals target 12.3 |

*Table 4:* **Measures considered for reducing environmental effects of food production**

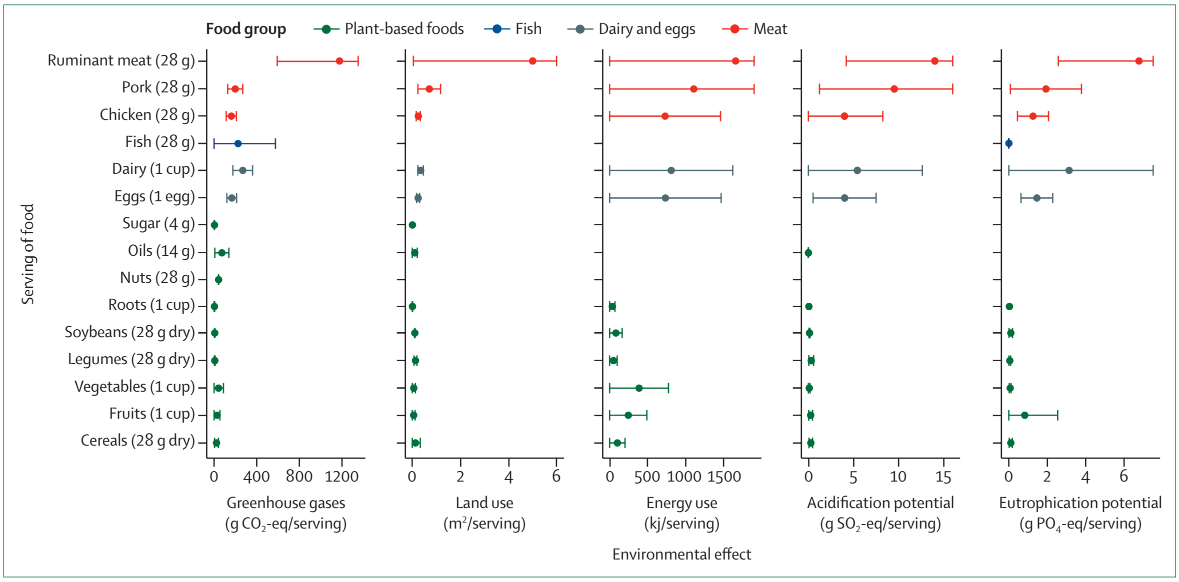


***Figure 4:* Environmental effects per serving of food produced**

Bars are mean (SD).[5,216] Some results are missing for fish due to lack of data for some impact categories (eg, land use stemming from plant-based feeds in aquaculture). This was, however, accounted for in the global food systems modeling framework used in Section 3. $CO_2$=carbon dioxide. Eq=equivalent. $PO_4$=phosphate. $SO_2$=sulphur dioxide.

## Scenarios for achieving healthy diets from sustainable food systems

To analyse environmental effects of various measures on each boundary of food production, we use a global food systems model with country-level detail that converts consumption patterns, such as the healthy reference diet, into associated requirements of food production (table 4). The model considers existing and future projections of food demand, trade, requirements of livestock feed, processing of oilseeds and sugar crops, and non-food demands for agricultural products by industry. A full description of the model is provided in the appendix (pp 19–23) and by Springmann and colleagues.[187] Here we extend the analysis by considering a broad set of dietary scenarios and sensitivity analyses.

To assess the environmental effects of food consumption, we paired the model's projections for food consumption for 2050 with country-level environmental footprints that we obtained from various sources (appendix p 24).[211,223–225] Our results show that animal source foods have large environmental footprints per serving for greenhouse-gas emissions, cropland use, water use, and nitrogen and phosphorus application, which supports study findings.[32] Total environmental effects are determined by combining region-specific environmental footprints per unit of food with estimates of food demand.

Future demand of food in this model is affected by changes in population size and income (ie, GDP). Population size changes the absolute quantity of food produced and income affects the types of foods produced. With increasing income, consumption of animal source foods, such as meat and dairy, and fruits and vegetables is expected to increase.[226] Our baseline (business-as-usual) projections follow a moderate socioeconomic development pathway (appendix p 1), whereby global population is projected to grow by a third and income is projected to triple.[211] For the business-as-usual scenario, we project that food production could increase greenhouse-gas emissions, cropland use, freshwater use, and nitrogen and phosphorus application by 50–90% from 2010 to 2050 in absence of dedicated mitigation measures.[187] This increase would push key biophysical processes that regulate the state of the Earth system beyond the boundaries and safe operating space for food production (figure 5). Different food groups affect the environment to different extents: animal source foods are responsible for about three-quarters of climate change effects, whereas staple crops, such as wheat, rice, and other cereals, are responsible for a third to a half of pressures on other environmental domains.

Several measures reduce environmental effects of food production. For our analysis, we grouped these measures into three categories: dietary changes towards healthy diets, technological and management-related changes in food production, and reductions in food loss and waste that involve technical changes (related to food loss during production) and behavioural changes (related to food waste at the point of consumption). The measures we considered (table 4) have been proposed in research literature and some have been declared as global or national goals (eg, reductions in food loss and waste).[27] We focused on measures that are feasible with existing technologies but have not been widely implemented.

Our analysis shows that to stay within the safe operating space for food systems, a combination of dietary changes and production and management-related measures are required (figure 6). Although implementation of some

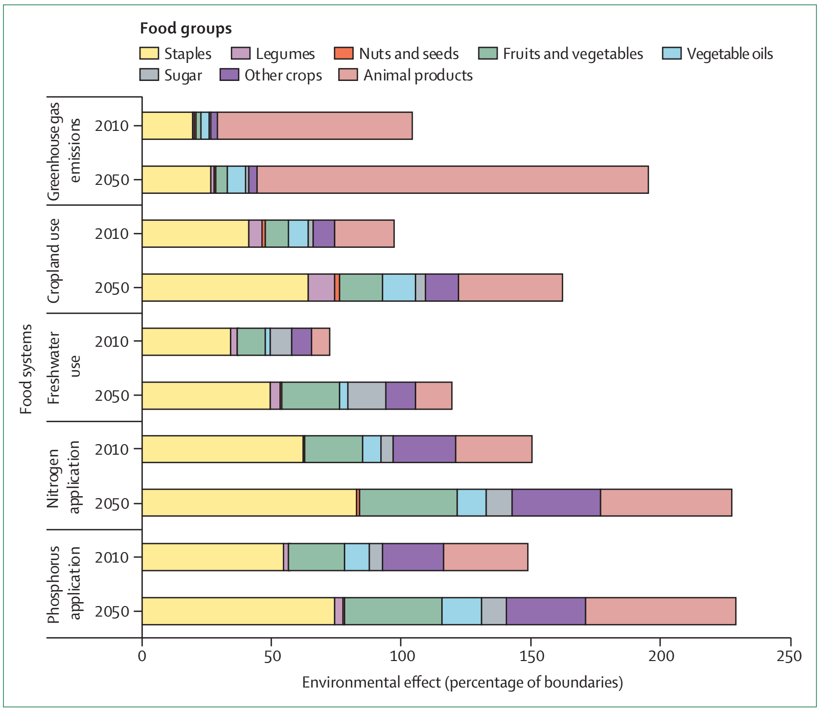


*Figure 5:* **Environmental effects in 2010 and 2050 by food groups on various Earth systems based on business-as-usual projections for consumption and production**

measures are sufficient to stay within particular boundaries, no single intervention is enough to stay within all boundaries simultaneously.

*Climate change*

Several studies have analysed measures to reduce greenhouse-gas emissions associated with food production. Although food production practices have an important role,[213,220,227] many studies highlight that a dietary change towards increased adoption of plant-based diets has high mitigation potential, which is probably needed to limit global warming to a less than 2°C increase.[5,6,228] Improved production practices to reduce greenhouse-gas emissions include changes in irrigation, cropping, and fertilisation, which can reduce methane and nitrous oxide emissions from rice and other crops, as well as changes in manure management, feed conversion, and feed additives, which can reduce enteric fermentation in livestock.[213] We estimated that changes in food production practices could reduce agricultural greenhouse-gas emissions in 2050 by about 10%, whereas increased consumption of plant-based diets could reduce emissions by up to 80%.[187] A further 5% reduction could be achieved by halving food loss and waste.

Staying within the boundary for climate change can be achieved by consuming plant-based diets. Improved production practices are less effective than a shift to healthy diets in abating food-related greenhouse-gas emissions because most emissions are associated with production of animal source foods whose characteristics, such as enteric fermentation in ruminants, have little potential for change. Increasing shift toward more plant-based diets will enable food production to stay within the climate change boundary.

*Land-system change*

Future land-use changes depend greatly on agricultural yields (ie, the output of food production per area) and the composition of crops that are demanded and produced,[140,144,184,226] which in turn are influenced by dietary choices and changes in technologies and crop management. It has been estimated that current yield trends are insufficient to meet global demand for wheat, maize, rice, and soybean if trends continue towards diets that are high in animal source foods.[229] Currently, almost two thirds of all soybeans, maize, barley, and about a third of all grains are used as feed for animals, so reductions in the portion of animal products in our diets would make the cropland associated with feed production available for other uses.[144] However, whether changing dietary preferences would result in a net decrease in the use of cropland depends also on the yields of the replacing crops, and those Differences in yield might not be as favourable as one might expect, considering that investments in high-yielding varieties have been primarily directed towards major grains over the last half century.[230,231] Our dietary scenarios include large amounts of nutritionally important but lower yielding crops, such as legumes and nuts.[144]

Our results indeed portray a complex picture.[187] The impacts of dietary changes resulted in small reductions in cropland use of 0–2%. The reason that we did not observe greater reductions from dietary change alone was that the reductions in cropland demand by countries with high portions of animal source foods were compensated by increases in cropland demand by countries that consume poor quality diets high in grains. By food group, the reductions in cropland use for feed crops was, to a large extent, compensated by large increases in cropland use for legumes and nuts which are relatively low-yielding. Redirecting investments towards higher-yielding varieties of those crops could be an effective strategy for reducing cropland use in the context of changes towards healthier diets which contain larger amounts of legumes and nuts. Our estimates of projected yield trends, and of changes in food loss and waste are more straight-forward. Based on data on yield trends and potential yield improvements across regions, we estimated that no cropland expansion will be needed if current yield gaps (ie, the difference between current and attainable yields) were closed to about 75% and food loss and waste was halved. Adopting even more ambitious levels of production improvements in combination with dietary shifts and reductions in food loss and waste would result in a net contraction of cropland use (panel 5).

*Freshwater use*

Previous studies have highlighted the potential of increasing water-use efficiency by improving water

| Production (2050) | Waste (2050) | Diet (2050) | Greenhouse-gas emissions (Gt $CO_2$-eq/yr) | Cropland use (M $km^2$) | Water use (M $km^3$) | Nitrogen application (Tg) | Phosphorus application (Tg) | OPTM biodiversity loss (E/MSY) | MAN biodiversity loss (E/MSY) | OPTN biodiversity loss (E/MSY) | NAT biodiversity loss (E/MSY) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Food production boundary | | | 5·0 (4·7–5·4) | 13 (11·0–15·0) | 2·5 (1·0–4·0) | 90 (65·0–140·0) | 8 (6·0–16·0) | 10 (1–80) | 10 (1–80) | 10 (1–80) | 10 (1–80) |
| Baseline in 2010 | | | 5·2 | 12·6 | 1·8 | 131·8 | 17·9 | 100 | 100 | 100 | 100 |
| | | | .. | .. | .. | .. | .. | .. | .. | .. | .. |
| (1) | | | | | | | | | | | |
| BAU | full waste | BAU | 9·8 | 21·1 | 3·0 | 199·5 | 27·5 | 2 | 36 | 153 | 1067 |
| BAU | full waste | reference | 5·0 | 21·1 | 3·0 | 191·4 | 25·5 | 2 | 45 | 120 | 1309 |
| BAU | full waste | pescatarian | 3·2 | 20·6 | 3·0 | 189·7 | 25·3 | 2 | 46 | 118 | 1313 |
| BAU | full waste | vegetarian | 3·2 | 20·8 | 3·1 | 186·9 | 24·7 | 2 | 48 | 122 | 1374 |
| BAU | full waste | vegan | 2·1 | 20·7 | 3·3 | 184·1 | 24·4 | 2 | 50 | 128 | 1431 |
| (2) | | | | | | | | | | | |
| BAU | halve waste | BAU | 9·2 | 18·2 | 2·6 | 171·0 | 23·2 | 1 | 24 | 105 | 716 |
| BAU | halve waste | reference | 4·5 | 18·1 | 2·6 | 162·6 | 21·2 | 2 | 32 | 81 | 940 |
| BAU | halve waste | pescatarian | 2·7 | 17·6 | 2·6 | 160·0 | 20·8 | 2 | 33 | 78 | 940 |
| BAU | halve waste | vegetarian | 2·7 | 17·8 | 2·7 | 158·5 | 20·5 | 2 | 35 | 83 | 1000 |
| BAU | halve waste | vegan | 1·7 | 17·7 | 2·8 | 155·0 | 20·0 | 2 | 36 | 90 | 1051 |
| (3) | | | | | | | | | | | |
| PROD | full waste | BAU | 8·9 | 14·8 | 2·2 | 187·3 | 25·5 | 1 | 7 | 68 | 237 |
| PROD | full waste | reference | 4·5 | 14·8 | 2·2 | 179·5 | 24·1 | 1 | 14 | 54 | 414 |
| PROD | full waste | pescatarian | 2·9 | 14·6 | 2·2 | 178·2 | 24·0 | 1 | 15 | 54 | 426 |
| PROD | full waste | vegetarian | 2·9 | 14·6 | 2·2 | 175·5 | 23·6 | 1 | 15 | 56 | 462 |
| PROD | full waste | vegan | 2·0 | 14·4 | 2·3 | 172·8 | 23·4 | 1 | 17 | 59 | 507 |
| (4) | | | | | | | | | | | |
| PROD | halve waste | BAU | 8·3 | 12·7 | 1·9 | 160·1 | 21·5 | 0 | 3 | 41 | 103 |
| PROD | halve waste | reference | 4·1 | 12·7 | 1·9 | 151·7 | 20·0 | 1 | 9 | 33 | 270 |
| PROD | halve waste | pescatarian | 2·5 | 12·4 | 1·9 | 149·3 | 19·8 | 1 | 9 | 34 | 281 |
| PROD | halve waste | vegetarian | 2·5 | 12·5 | 1·9 | 148·0 | 19·5 | 1 | 10 | 36 | 317 |
| PROD | halve waste | vegan | 1·6 | 12·3 | 2·0 | 144·6 | 19·2 | 1 | 12 | 40 | 358 |
| (5) | | | | | | | | | | | |
| PROD+ | full waste | BAU | 8·7 | 13·1 | 2·2 | 147·6 | 16·5 | 1 | 10 | 61 | 292 |
| PROD+ | full waste | reference | 4·4 | 12·8 | 2·1 | 140·8 | 15·4 | 1 | 14 | 47 | 414 |
| PROD+ | full waste | pescatarian | 2·8 | 12·4 | 2·2 | 139·3 | 15·3 | 1 | 15 | 46 | 424 |
| PROD+ | full waste | vegetarian | 2·8 | 12·5 | 2·2 | 136·6 | 14·8 | 1 | 16 | 47 | 456 |
| PROD+ | full waste | vegan | 1·9 | 12·3 | 2·3 | 133·5 | 14·4 | 1 | 17 | 49 | 494 |
| (6) | | | | | | | | | | | |
| PROD+ | halve waste | BAU | 8·1 | 11·3 | 1·9 | 128·2 | 14·2 | 0 | 7 | 38 | 196 |
| PROD+ | halve waste | reference | 4·0 | 11·0 | 1·9 | 121·3 | 13·1 | 0 | 10 | 28 | 290 |
| PROD+ | halve waste | pescatarian | 2·4 | 10·6 | 1·9 | 118·8 | 12·9 | 0 | 10 | 27 | 298 |
| PROD+ | halve waste | vegetarian | 2·4 | 10·7 | 1·9 | 117·6 | 12·6 | 0 | 11 | 29 | 330 |
| PROD+ | halve waste | vegan | 1·5 | 10·5 | 2·0 | 113·9 | 12·1 | 0 | 12 | 33 | 366 |

***Figure 6:* Various scenarios demonstrating the environmental effects of implementing measures considered for reducing environmental effects of food production**

Colours indicate whether environmental effects transgress food production boundaries. Red cells indicate above upper range value. Orange cells indicate above boundary but below upper range value. Light green cells indicate below or equal to boundary but above lower range value. Scenarios increase in ambition from 1 to 6, with 1 being low and 6 being high. Gt $CO_2$-eq/yr=Gt of carbon dioxide equivalent per year. OPTM=optimisation managed habitat. E/MSY=extinctions per million species-years. MAN=managed or secondary habitat. OPTN=optimisation natural habitat. NAT=natural habitat. BAU=business as usual. PROD=improved production practice. PROD+=improved production practice+.

management and technologies, such as irrigation systems,[232] as well as by dietary change towards diets lower in animal products.[233] Using data from basin-scale hydrological models,[211] we estimated that improved production practices could reduce water use by about 30%, and halving food loss and waste could reduce water use by about 13%.[187] For dietary changes, we identified similar trade-offs as for cropland use, water use could increase by 1–9% as reductions related to lower consumption of animal products and sugar are overcompensated by increases related to greater consumption of nuts and legumes. The lower end of the reductions is for the more plant-based scenarios that include larger amounts of water-intensive nuts and legumes.

According to our estimates, staying within the planetary boundary for water use can be achieved by combining improvements in water-use efficiency with reductions in food loss and waste. However, our analysis does not highlight regions or nations that currently face water shortage and are already above regional or national boundaries for EFRs. This is discussed in more detail in chapter 3 and the appendix (p 17).

*Nitrogen and phosphorus application*

The reduction of effects related to the overapplication of nitrogen and phosphorus fertilisers is receiving increasing interest. The discussed measures include technology-driven increases in use efficiencies,[234]

### *Panel 5:* The future of food in the face of climate change

Most studies investigating the effect of climate change on food production indicate an aggregate reduction in future agricultural productivity, particularly in low-latitude regions.[A24–A27] Knox and colleagues[A24] project an 8% reduction in mean yield of all crops by 2050 across Africa and south Asia. For major crops (wheat, rice, and maize) in tropical and temperate regions, local temperature increases of 2°C or more without adaptation will negatively affect production. However, substantial variability exists between regions, crops, and adaptation scenarios. About 10% of projections for 2030–49 show more than 10% increase in food production, whereas about 10% of projections show more than 25% decrease,[A25] with risks of more severe effects increasing after 2050.

Climate change will also affect fisheries and aquaculture.[A28–A30] Increased productivity is estimated at high latitudes and decreased productivity at low and mid latitudes, with considerable regional variation. For example, poleward migration of fish alone has been estimated to reduce maximum catch potential in some tropical areas by up to 40%.[A31] However, deviation from current yields rarely exceeds 10%.[A32]

The effects of climate change on agriculture are expected to substantially impact human health. Reductions in agricultural production due to climate change have been estimated to cause 500 000 climate-related deaths in 2050, most of which are due to reduced fruit and vegetable production and consumption, followed by increases in underweight from reduced availability of food.[A33] In addition, nutritional quality of food and fodder is predicted to decrease because of elevated carbon dioxide concentrations.[A25] For example, grains and legumes contain lower concentrations of iron and zinc when grown at elevated carbon dioxide concentrations that are predicted for mid-century than do grains and legumes grown at current carbon dioxide concentrations.[A34] At elevated carbon dioxide concentrations, protein and amino acid concentrations decrease in spring wheat (a major staple crop), whereas non-structural carbohydrates (except starch) and lipids significantly increases.[A35]

Crop diversity might be a solution to decreasing yields and nutritional quality caused by climate change. A report by the Food and Agriculture Organization places crop diversity at the forefront of adaptation solutions.[A36] New and improved crop varieties are needed that can withstand challenges that climate change will pose to global food security. Developing crop varieties that can withstand heat, drought, flood, and other extreme weather events might be the most important step to adapt to climate change.

References cited in this panel can be found in the appendix (pp 27–28).

improvements in management of livestock and manure,[235–237] improvements in fertiliser application and distribution,[184,232,237] reductions in household waste,[236] nutrient recycling (eg, through improvements in sewage systems),[214] and dietary changes towards diets with few animal products.[236] In our analysis, we represented various mitigation strategies by increases in use efficiencies, improvements in fertiliser application and distribution, and dietary changes.[187] We estimated that increased use efficiencies and optimised application of fertilisers, including recycling of phosphorus and rebalancing between regions that overapply fertiliser and those that underapply could reduce nitrogen use by about 26% and phosphorus use up to 40%. Reductions in food loss and waste could reduce use of each nutrient by up to 15%, and dietary change towards healthy diets could reduce total application needs by about 10%. Staying below the upper ranges for nitrogen and phosphorus required the most ambitious improvements in food production practices, dietary shifts, and reductions in food loss and waste. The challenge of staying below the boundaries for nitrogen and phosphorus highlights the need to identify further ways to control their use.

#### *Biodiversity*

Studies have investigated the effect of increasing agricultural expansion on biodiversity loss, especially in tropical countries where biodiversity is highest.[16,190,197] Biodiversity loss is most severe when natural habitat (eg, primary tropical forest) is converted to agricultural land, especially when compared with conversion of secondary or degraded habitats: our results support this finding (figure 6).

We found that cropland use and extinction rates were synergistic, with greatest reductions occurring with improved production practices and reductions in food loss and waste. Projected extinctions in our analysis show high spatial variation, with many extinctions projected to occur in tropical countries and island countries with high richness of endemic species. Projected future extinction rates exceed extinction rates of the past century[195] if cropland expansion occurs at the cost of existing primary habitat.

Extinction risk can be reduced through various measures. First, expanding cropland into existing secondary habitat (eg, logged forests and plantations) or other managed ecosystems (eg, pastures and rangelands) reduces the number of species lost by more than 90%. Second, adopting technologies and management-related changes reduces cropland expansion and has the greatest potential of reducing global biodiversity loss (about 75% relative to business-as-usual scenario). Third, halving food loss and waste can reduce projected biodiversity loss by up to 33% relative to the business-as-usual scenario and has a smaller potential than other measures (ie, dietary shifts and improved production practices) to benefit biodiversity.

We found that adopting the reference diet (or one of its variations) could increase the global number of extinctions if land-use change occurs in areas of food production. This effect is mainly a result of increased caloric intake to 2500 kcal/capita per day in the reference diet in countries where caloric intake is lower than this value, and shifting production priorities to produce crops (eg, nuts and pulses) needed to support the reference diet. However, these results assume that domestic production will meet a proportion of the additional demand. Rebalancing regional production on the basis of biodiversity concerns could mitigate those additional stresses and have the greatest effect on reducing biodiversity loss (figure 6).[144,206] Results from all of our optimisation scenarios can be found in the appendix (p 25). In addition, biodiversity data that integrates the impact of expansion into managed habitat and land optimisation into a single set of data can be found in the appendix (p 26).

| Production (2050) | Waste (2050) | Diet (2050) | Greenhouse-gas emissions (Gt $CO_2$-eq/yr) | Cropland use (M km$^2$) | Water use (M km$^3$) | Nitrogen application (Tg) | Phosphorus application (Tg) | OPTM biodiversity loss (E/MSY) | MAN biodiversity loss (E/MSY) | OPTN biodiversity loss (E/MSY) | NAT biodiversity loss (E/MSY) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Food production boundary | | | 5·0 (4·7–5·4) | 13 (11·0–15·0) | 2·5 (1·0–4·0) | 90 (65·0–140·0) | 8 (6·0–16·0) | 10 (1–80) | 10 (1–80) | 10 (1–80) | 10 (1–80) |
| | | | .. | .. | .. | .. | .. | .. | .. | .. | .. |
| BAU | halve waste | ref high meat | 6·7 | 18·7 | 2·8 | 168·9 | 23·0 | 2 | 36 | 108 | 1029 |
| PROD | halve waste | ref high meat | 6·0 | 13·0 | 2·0 | 158·7 | 21·4 | 1 | 9 | 41 | 268 |
| PROD+ | halve waste | ref high meat | 5·9 | 11·5 | 2·0 | 127·0 | 14·2 | 0 | 15 | 37 | 403 |
| BAU | halve waste | ref low cal | 4·3 | 16·1 | 2·3 | 147·2 | 19·0 | 1 | 22 | 81 | 647 |
| PROD | halve waste | ref low cal | 3·3 | 11·4 | 1·6 | 137·3 | 18·1 | 1 | 8 | 33 | 246 |
| PROD+ | halve waste | ref low cal | 3·8 | 9·7 | 1·6 | 109·3 | 11·6 | 0 | 5 | 28 | 170 |
| BAU | halve waste | ref high milk | 6·7 | 18·8 | 2·6 | 171·3 | 22·7 | 2 | 34 | 109 | 983 |
| PROD | halve waste | ref high milk | 6·0 | 13·3 | 1·9 | 161·4 | 21·4 | 1 | 10 | 43 | 299 |
| PROD+ | halve waste | ref high milk | 5·8 | 11·4 | 1·9 | 130·0 | 14·3 | 1 | 11 | 39 | 309 |

***Figure 7*: Environmental effects of increased meat (ref high meat) and milk (ref high milk) consumption above those described by the reference diet and reduced caloric intake to 2100 kcal/day (ref low cal)**

Colours indicate whether environmental effects transgress food production boundaries. Red cells indicate above upper range value. Orange cells indicate above boundary but below upper range value. Light green cells indicate below or equal to boundary but above lower range value. Dark green cells indicate below lower range value. Gt $CO_2$-eq/yr=Gt of carbon dioxide equivalent per year. OPTM=optimisation managed habitat. E/MSY=extinctions per million species-years. MAN=managed or secondary habitat. OPTN=optimisation natural habitat. NAT=natural habitat. BAU=business as usual. PROD=improved production practice. PROD+=improved production practice +.

Staying below the upper range for biodiversity required the most ambitious improvements in food production practices, dietary shifts, and reductions in food loss and waste and getting near the boundary only happened in the most ambitious scenarios. The challenge of staying below the biodiversity boundary highlights the need to implement additional measures. These include establishment of new protected areas,[238] expansion and increased enforcement of protected areas in key biodiversity areas,[238] increasing international trade from high yielding nations with low biodiversity to low yielding nations with high biodiversity,[16,202,203] and minimising agricultural expansion into species rich areas.

## Sensitivity analysis

We did a series of sensitivity analyses to identify additional dietary aspects of importance for staying within boundaries for food production. For that purpose, we varied the composition of the reference diet by changing its meat and dairy content and assessed the importance of scale effects by considering a scenario of low caloric intake (figure 7). Increasing the limit on red meat intake from one 100 g serving per week to three servings (the limit put forward by the World Cancer Research Fund for lowering cancer-related risks of red meat consumption)[239] increased food-related green house-gas emissions by nearly 50% and also increased other environmental effects compared with the same scenarios found in figure 6. Increasing milk consumption from 250 g/day in the reference diet to 500 g/day (a level less than dietary guidelines in the USA) increased greenhouse-gas emissions and total environmental effects. Neither scenario could be combined with improvements in production practices to become a feasible combination that would stay within the boundaries for food production. By contrast, reducing caloric intake from 2500 kcal/day to 2100 kcal/day, an intake assuming that BMI is reduced to 22 kg/m² globally, which complies with WHO recommendations on healthy bodyweight and physical activity levels,[240] slightly reduced environmental effects when compared with the same scenarios in figure 6.

Global use of the reference diet would have important implications for food production (figure 8). By contrast with the business-as-usual model, production of grains would change minimally from 2010, and production of beef, pork, and lamb would decrease. Production of sugar, milk, poultry, and eggs would change minimally, and production of fruits, vegetables, legumes, nuts, soybeans, oil crops, and fish would increase substantially (panel 6). These changes contradict projections widely used by international organisations that have emphasised large increases in grain production to feed an increased population of animals.[241] According to our analysis, these projections would substantially exceed food production boundaries and highlight the urgency for using scientific targets to guide transformation of the food system.

## Uncertainty in modelling results

We have a higher level of certainty in the overall direction and approximate magnitude of the relationships presented in figure 6 than we do about specific quantitative details. For example, we can be certain about the trend of decreasing rates of biodiversity loss with dietary changes and improved production practices. However, we are less certain about the exact number of species that will be lost in each scenario and dietary change. This is also the case for other control variables: we are less certain about exact numbers resulting from each scenario but have higher certainty in the trends of decreasing environmental effect with improvements in production practices, reduction in food loss and waste, and shifts towards healthy diets.

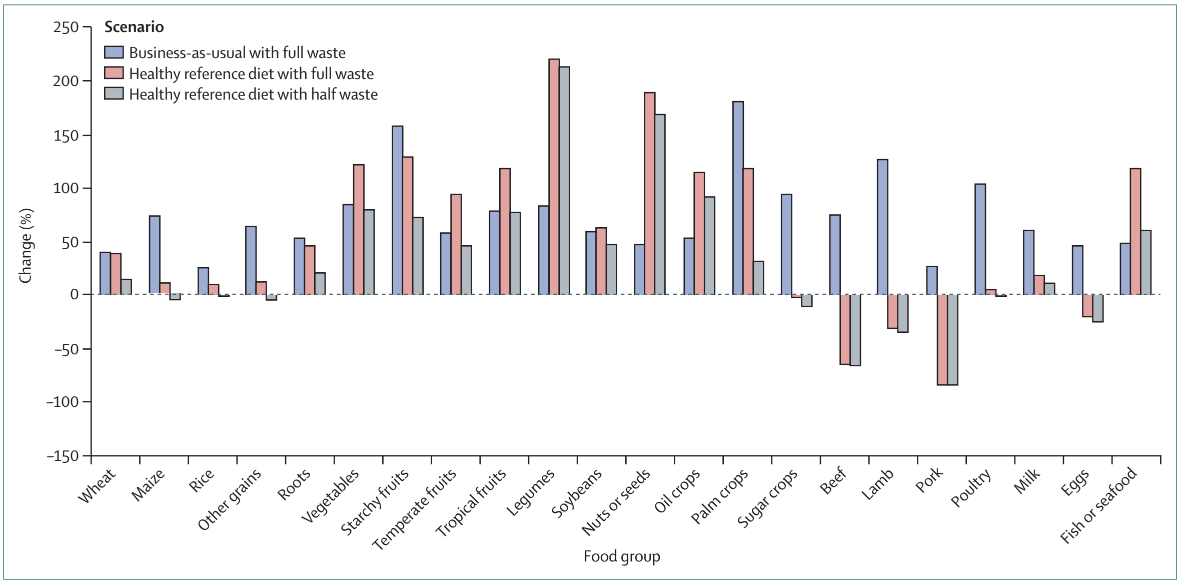


*Figure 8:* **Predicted change in production from 2010 to 2050 for the business-as-usual with full waste scenario and the healthy reference diet with full or half waste scenarios**

### *Panel 6:* The role of seafood in global diets

Seafood provides 3·1 billion people with about 20% of their daily intake of animal protein and is particularly important for the world's poorest for whom fish eaten whole constitute a crucial source of essential micro nutrients.[A37,A38] With 90% of global wild fish stocks being overfished or fished at capacity, seafood extraction potential from the wild has probably reached a ceiling[A38] or is declining.[A39] Future expansion of seafood should come from aquaculture, which is one of the fastest growing food production sectors in the world. However, such rapid development can also have negative environmental and social effects including habitat destruction, overfishing for feed ingredients, and social displacement.[A40]

Aquaculture production is projected to increase from 60 million tons in 2010 to 100 Mt in 2030,[A41] and up to 140 Mt by 2050.[A42] Key constraints include competition for feed resources[A40] and available land for freshwater farming. Research in sustainable aquaculture feeds is rapidly developing; however, development and implementation still remains in its infancy.[A43] Farmed non-feed dependent animal species (ie, mussels and oysters) might be a more sustainable alternative than farmed feed-dependent species and account for 31% of global aquaculture production.[A38] However, future development might be hampered by deteriorating water quality due to pollution and ocean acidification.

The future environmental footprint of seafood depends on the species farmed, what they eat, and where aquaculture takes place. Aquaculture will not solve the challenges posed by feeding about 10 billion people healthy diets but could help steer production of animal source proteins towards reduced environmental effects and enhanced health benefits.

References cited in this panel can be found in the appendix (pp 27–28).

We did not investigate the role of innovative technologies that are not yet proven at scale but might become operational in the future because of the paucity of data available on the environmental effects of those technologies. Some examples of potential innovative techniques include using insects, algae, and microbes as human or animal feed,[19] and laboratory-cultured meat.[242] In this Commission, we chose to focus on solutions that are readily available but might not have been implemented at scale.

## Section 4: Framework for a Great Food Transformation

### Lessons from past successful global transformations

This Commission does not underestimate the importance of its message or the urgency of the task it sets, which are in line with international reviews[4,243–253] of different aspects of global food systems over the past decade. The Commission highlights the need for a Great Food Transformation—ie, a substantial change in the structure and function of the global food system so that it operates with different core processes and feedback. This transformation will not happen unless there is widespread, multi-sector, multi-level action to change what food is eaten, how it is produced, and its effects on the environment and health, while providing healthy diets for the global population.

Solutions to the problems highlighted by the Commission will require hard work, political will, and many resources. People might warn of unintended consequences or argue the case for action is premature or should be left to existing dynamics; however, we disagree. Data are sufficient and strong enough to warrant action, and delay will increase the likelihood of serious, even disastrous, consequences. The approaches taken in the Great Food Transformation should be guided by scientific targets that define the safe operating space for food systems: the combination of healthy diets and planetary systems and processes, which underpin human health and environmental sustainability.

Humanity has never aimed to change the food system so radically at this scale or speed. In the 20th century, major transformations have occurred in the national food system in countries such as China, Brazil, Vietnam,

| | Location | Problem | Timing | Action | Multilevel intervention | Success? |
|---|---|---|---|---|---|---|
| Food supply | Global | 1920s and 1930s food system exhibited major problems of hunger, inequality, environmental damage, and political upheaval | The US Dust Bowl;[259,260] recession-led hunger and famine, exacerbated by war (eg, Soviet Union 1932–33; Bengal, India; UK 1936)[261–264] | Hot Springs Conference 1943 began the mapping, food and Agriculture Organization of the UN created in 1945, and widespread food welfare programmes implemented (eg, in schools)[265] | Policy pressure from health, agriculture and social research combined with political will across ideological divides to build action at the global, national, and local (farm, citizen, and school) level | A transformation of world food supply followed, but it came at the cost subsequently noted as threats to ecosystems and the growth of new diet-related ill health |
| HIV/AIDS | Global | Approximately 70 million people affected since outbreak: 35 million deaths from HIV, and 36·7 million living with HIV/AIDS[266] | Almost certainly first emerged in the 1940s, and identified with male-to-male sex in the USA in 1970s | Virus identified in 1983; antiretroviral therapy developed (19·5 million people vaccinated in 2016); prevention of mother-child transmission; and facilities for testing and counselling established[266] | Sound data and research, mass education programmes, peer-to-peer learning, pharmaceutical development, and finance support | Containment is possible; no eradication yet; more success in affluent countries with infrastructural support |
| Tobacco controls | Global | Causal link between smoking tobacco and premature death from preventable disease | Causal link between smoking tobacco and lung cancer shown in 1952 | Years of action lead to WHO Framework on Tobacco Control, a treaty adopted at 56th World Health Assembly, May 2003—the first WHO treaty adopted under article 19 of the WHO constitution | Decades of research showing link between smoking and disease, patient organisation neutralising opposition, a mix of fiscal and educational programmes, and a mix of actions from global to individual[267] | Clear evidence for action plus wide support for controls but the product is still legally available and widely used |
| Trans fatty acids in the food supply | Global | Industrially produced trans fatty acids (trans fats) contribute to premature death from heart disease of 500 000 people annually[268] | First noted in 1950s,[269] with 1970s research meeting strong resistance from vested interests, solid research from the 1980s showed the health effect of trans fats[270] | 2015 decision by US Food and Drug Administration to ban trans fats; 2018 call by WHO for global elimination; and restrictions or bans in Denmark, Switzerland, Canada, Britain, and USA | Public health concerns are beyond doubt, WHO endorses a REPLACE strategy, and food industries recognise alternatives | The movement to remove or reduce trans fats, or both, is accelerating worldwide |
| Energy shift | Global | Fossil fuels are a source of greenhouse-gas emissions, and were noted as potential disruptors of the carbon cycle | Oil becomes major fuel source in mid 19th century; the assumption that oceans would absorb excess carbon was questioned in late 1950s | Alternative energy research and development; public awareness; scientific monitoring of climate change (eg, Intergovernmental Panel on Climate Change)[271] | Research data, technology development, rise of renewable energy, cheaper alternatives, and a mix of mass and localised actions and interventions | Fossil fuel use still high but rise of renewables now considered a major and growing feature of energy provision[272] |
| Effect of fertiliser use on water quality | Global | Indiscriminate use by farmers; high cost; environmental effects (eg, run-off)[273] | Concerns about the effect of nitrogen run-off on various outcomes ranging from blue baby syndrome, to biodiversity loss and water pollution | A systemic approach was adopted by the EU in the 1991 Nitrate Directive and 2000 Water Framework Directive These reduced nitrogen fertiliser use by 19% in 1990–2010[274] | Inefficient use, cost savings, strong regulatory framework, public pressures, and water companies working with farmers to prevent overuse | Fertiliser use is rising again in the EU but dropping in some countries, leading to pressure to target use more efficiently[275] |

EU=European Union.

***Table 5:*** **Reasons to be cheerful: examples of systems change and systemic action**

and Finland,[254–256] and lessons can be learnt from these transformations. The world's diet can change rapidly. In the past few decades, countries have changed diets and gone through a nutrition transition. The health effects of some of these transitions, such as increased consumption of sugar, are beginning to show.[257]

Wars and disasters cause food insecurity and highlight the issues faced when nutrition is inadequate and food becomes scarce. Wars and natural disasters also provide opportunities from which the food system can be transformed. However, only at the end of World War 2 was a global effort and commitment introduced to redirect the food system.[258] New institutions were created or revised at the global level such as WHO, the Food and Agriculture Organization, and World Bank, which allied with new and renewed national Ministries of agriculture and health to stop pre-war food problems caused by market distortions, environmentally-damaging farming, and social inequalities.[259] However, the negative consequences of the post-war food revolution are now becoming increasingly clear (ie, negative environmental and health consequences, as outlined in this Commission).

Our evidence offers the ability to anticipate events and shape better outcomes. Table 5 lists some examples of when science has informed or led global transformations. However, these transformations are not as extensive as is required by the Great Food Transformation, but optimism and lessons can be derived. The first lesson from past global transformations is that no single actor or breakthrough is likely to catalyse systems change. Systems change is extensive and will therefore require engagement of actors at all scales and in all sectors working towards a shared set of goals. This lesson is fundamental to Sustainable Development Goal 17, which recognises that "A successful sustainable development agenda requires partnerships between governments, the private sector and civil society. These inclusive partnerships built upon principles and values, a shared vision, and shared goals that place people and the planet at the centre, are needed at the global, regional, national and local level."

| | Description | Indicative government role | Indicative industry role | Indicative civil society role |
|---|---|---|---|---|
| Eliminate choice | Channel actions only to the desired end and isolate inappropriate actions | Set goals for a zero or negative-effect food system | Withdraw inappropriate products; diversify the business | Win public support for elimination of unhealthy diets |
| Restrict choice | Remove inappropriate choice options | Model choice editing or rationing on a population scale | Allocate funding to favour sustainable and healthy products | Campaign for banning and pariah status of key products and processes |
| Guide choices through disincentives | Apply taxes or charges | Develop multicriteria interventions, building on existing developments such as carbon and sugar taxation, and scoping others such as marketing controls, carbon-calorie connections | Use of contracts and conditions to shape supply chains | Disinvestment campaigns |
| Guide choices through incentives | Use regulations or financial incentives | Interagency, cross-government engagement with the consuming public | Consumer reward schemes | Build cultural appeal for healthy diets from sustainable food systems |
| Guide choice by changing default policy | Provide better options | Recognise the problem but not give it high priority | Already being pioneered by retailers in their own-label products, and by in food service actors through menu planning, reformulation | Legislative change campaigns |
| Enable choice | Enable individuals to change behaviour | The market economics position, currently manifest via logos and branding appeals | Focused marketing on only healthy and sustainably produced foods | Campaign for alternative products |
| Provide information | Inform or educate the public | Mass, public information campaigns | Prioritisation of brands which appeal to eat differently, | Led by NGOs, brands and some commercial interests |
| Do nothing | No action or only monitor situation | The all-too common baseline of inactivity, which can be maintained by vested interest support | Rely on public relations or media advisers to alert as to coming difficulties | Ignore the wider picture and stick to narrow spheres of interest |

Interventions are hard to soft from top to bottom.[276] NGO=Non-governmental organisation.

*Table 6:* **Applying the Nuffield Ladder of Policy Intervention to Health Diets from Sustainable Food Systems**

Second, scientific research is essential to change the global food system. The gap between evidence of problems with the food system and policy leverage to induce change should be acknowledged. However, modelling suggests the goal of providing healthy diets for the global population from sustainable food systems can be met, and 10 billion people could be fed a healthy and sustainable diet. The present unhealthy, unequal, unsustainable food system can be transformed into an improved system. Interdisciplinary research and monitoring will be essential in this process, not least to maintain the scale and pace of change. Although long-term research is important, short-term research is urgently needed to help policy actors to operate on a strong evidence base.

Third, the full range of policy levers is likely to be needed (table 6).[277] Faced with challenges, policy makers might initially implement soft policy interventions, such as consumer advice, information, education, or, in the case of food, labelling. These interventions assume that consumer actions will generate sufficient change[278] and are slow in effect unless mass public interest in change exists. However, the scale of change to the food system is unlikely to be successful if left to the individual or the whim of consumer choice. This change requires reframing at the population and systemic level. By contrast, hard policy interventions include laws, fiscal measures, subsidies and penalties, trade reconfiguration, and other economic and structural measures. These interventions alter conditions in which the whole population exists. The type of interventions adopted is the prerogative of governments, people, and processes. However, countries and authorities should not restrict themselves to narrow measures or soft interventions. Too often policy remains at the soft end of the policy ladder.

The policy terrain indicated by this Commission is broad. Some people argue that focusing on a few achievable targets is the best strategy. However, a shared, planetary overview requires a parallel, extensive, policy umbrella. Our vision, with scientific targets for healthy diets and sustainable food production, integrates food, health, and environmental policy into many policy areas, including trade, economics, rural livelihoods, equity, culture, society, and community. This inclusion is a strength, not a diffusion of effort. For the food system to change and for healthy diets to be available to all requires not only food production or consumption to change, but also active involvement of sectors in the middle of the food chain, such as food processing, storage, logistics, retail, and food service. These sectors need to be engaged in the transformation, not least because these intermediary sectors have economic power and cultural influence in food systems.[279,280] The Commission therefore calls for more work on these stages of global food systems.

## Five strategies for a Great Food Transformation

In addition to the lessons learnt from past global transformations, we established five readily implementable strategies and recommendations for how a sustainable food system transformation could be achieved. For each strategy, the evidence base is strong, and our modelling and analysis shows the potential effectiveness of these strategies for the achievement of a sustainable food system transformation. The strategies are proposals to begin processes. This Section does not provide an exhaustive nor prescriptive list of actions. Rather, these strategies are presented as indicative entry points for further context-specific national, regional, city, and local change.

*Strategy one: seek international and national commitment to shift towards healthy diets*

Concerted commitment from national and international bodies can be achieved by, first, improving the availability and access to healthy diets from sustainable food systems. Retailers and food services shape the immediate environment in which people buy food. In high-income societies, a priority is to offer less than what is currently offered by reducing portions, choice, and packaging, as well as introduce new, innovative packaging to preserve perishable foods. Whereas, low-income countries should increase the range and seasonality of foods by cutting waste on or near primary production, improving logistics and storage, and increasing the range and seasonality of foods. In high-income and low-income societies, standards of public and private sector procurement should be guided by the need to improve diets and access to outlets or vendors providing healthy products. Local authorities need powers to apply zoning regulations in low-income areas to restrict unhealthy food outlets.[281] Contracts and procurement policies can be used to promote healthy diets from sustainable food systems in workplaces, schools, and venues where public meals are provided, but these policies need persistence and continued political leadership for success. Multiple indicators of human and environmental health discussed in this Commission need to be applied. Public distribution programmes targeting low-income households and individuals can improve nutritional status.[282] Evidence that improved infrastructure or zoning regulations could increase healthy food consumption or reduce BMI is scarce, possibly because of poor policy or evaluation design and insufficient data. Further research is thus warranted in this area.[283] Urban planning interventions should account for local context and address ways in which residents of low-income areas interact with local food systems, such as their ability or desire to travel to different areas to buy food.[284]

In low-income countries, ensuring adequate infrastructure (eg, roads, bridges, and transportation) to remote or rural areas can improve access to sellers of healthy food and reduce food prices, food price volatility in local markets,[285] and food losses during transport. Agricultural extension programmes that focus on nutrition and food security can help ensure that rural farmers and women in rural households are equipped with the information and skills they need to obtain healthy diets from sustainable food systems.[286,287] In areas with informal markets, price incentives for street vendors to use healthy and sustainable ingredients and investment in sanitary locations for these outlets have been recommended to increase availability of safe, nutritious food.[253]

Second, healthy diets from sustainable food systems should be made affordable. Primary producers are locked into demands from suppliers to produce commodities cheaply but plentifully. Consumers value food being sufficiently low cost to enable them to make other domestic purchases. Low-income societies spend a high proportion of household budgets on food, whereas high-income societies spend a low proportion. Food prices are relative to social circumstance within and between societies. Increased affordability of consumer food has been a success of the post-World War 2 food revolution. Some foods are under pressure to increase in price to include externalities. Experimentation with sugar or soft drink taxes is one example.

We believe that food prices should fully reflect the true costs of food. Subsidies on fertilisers, water, fuels, electricity, and pesticides should be critically reviewed, with some authorities arguing for their removal, and environmental and societal health costs of food supply and consumption should be fully reflected in pricing by introducing taxes. As a result, food prices might increase. Therefore, where appropriate, social protection or safety nets (eg, increasing income through cash transfers) can be established to protect vulnerable populations, particularly children and women, while keeping trade open. We recommend an expert panel be set up to model different economic interventions, noting the work already underway from UN Environment Programme's initiative, The Economics of Ecosystems & Biodiversity for Agriculture and Food.[288] Taxes and subsidies should encourage healthy[289] and sustainable diets.[290] These measures combined limit the potentially regressive nature of either measure implemented in isolation.[291] Social protection or safety nets could substantially improve nutrition outcomes in low-income households, but these programmes should be explicitly nutrition-sensitive to be effective.[292]

In rural areas, increasing food security can improve access to and affordability of healthy diets from sustainable food systems. Access to economic resources and measures for poverty alleviation, particularly among women, are crucial for securing healthy diets from sustainable food systems. Market access and off-farm opportunities are essential for providing these rural farmers with the income needed to remain food secure.[293] Reducing volatility of food prices is important to ensure affordability of healthy diets from sustainable food systems, particularly at the regional or local level. Key policies to reduce this volatility include removing market barriers across local regions or markets, ensuring access to price information and early warning systems, implementing strict regulations against over-speculations, international management of food stocks, revisions of biofuel subsidies and tariffs to avoid diversion of food to energy use, and establishing social protection schemes, insurance programmes, and other safety nets.[294]

Third, renewed efforts by governments, industry, and society are required to restrict advertising and marketing of unhealthy, unsustainable foods, and to support positive discrimination of healthy diets from sustainable food systems. These efforts are in line with numerous calls from the 2013 WHO Global Action Plan, 2011 UN conference, 2010 WHO recommendations for marketing of food and non-alcoholic beverages to children, and the WHO Ending Childhood Obesity Commission.[295–298] The INFORMAS framework is a tool that civil society and researchers can use to monitor food labelling, promotion, and retail (among other) activities in a particular food environment and then compare those activities to best-practice for creating healthy food environments.[299]

Fourth, individuals should be educated on healthy diets from sustainable food systems. Although education campaigns are less effective than regulatory or fiscal measures in creating sustained change,[300] educational efforts might be a necessary precursor to strong intervention because of substantial barriers to implementing hard regulatory measures. Such education on healthy diets could be integrated into schools (eg, school feeding and school meal programmes), all national services, social protection programmes (eg, cash transfer programmes), and peer groups (eg, women farmer groups and co-operatives). Civil society groups, the media, and other leaders have an important role in increasing public knowledge of healthy diets from sustainable food systems through informational campaigns and starting social movements to shift diets or reduce food waste.

Dietary guidelines that integrate health and environmental sustainability considerations could be one tool for nutrition education. The introduction of such guidelines has been slow, and official dietary guidelines are still absent in many countries.[301] In countries with official advice, these guidelines are rarely followed through with enabling or enforcing legislation or other policies thus remaining as the softest form of consumer advice.[302] Relevant national bodies should implement guidelines for healthy diets from sustainable food systems, supported by enabling policies and incentives, and reflected through public procurement policies. Public sector organisations could work with non-governmental organisations progressing guidelines for healthy diets from sustainable food systems.[303,304]

Fifth, sustainable diets that taste good and are culturally appropriate should be promoted. Chefs and foodservice sectors increasingly recognise that they have an important role in the Great Food Transformation. Whether designing new menus,[305–307] taking a lead in national public campaigns about health and sustainability—as did 130 chefs from 38 countries on World Food Day on Oct 10, 2017, and did Nordic chefs with the New Nordic Kitchen Manifesto in 2004[308]—or pioneering peer-group education with other chefs via professional bodies,[309] the cooking and catering enterprise is essential for this public health change. Healthy, delicious, affordable food can be essential to mass dietary change. Consumers can and should like and help to drive the dietary shift.

Sixth, physicians and health-care service workers can engage with other industries to redesign public food provisions, such as school and hospital meals, and advise food service industries.[305] Because food preferences can develop during the first years of life and even during gestation,[310] nutrition counselling (ie, breastfeeding promotion and appropriate complementary feeding) should be integrated into maternal and child-care programmes. Since medical education largely omits the importance of nutrition to health, curricula should be revised and new training packages created that combine nutrition and ecosystems as determinants of health. Food services in health-care facilities could demonstrate to patients a high standard for healthy foods and beverages from sustainable food systems.

*Strategy two: reorient agricultural priorities from producing large quantities of food to producing healthy food*

Food policies need reframing to shift emphasis from high volumes of outputs to high diversity of crops and nutritional quality of foods produced. Researchers and public health professionals are calling for accurate data to track diet quality,[311] recommending improvement of diet quality assessments,[312] and emphasising the importance of diet quality to food security.[313] Resources should be directed to creating robust diet quality assessment tools, which could serve as an SDG indicator, with requisite capacity building and regular data gathering efforts at the country level. Emphasis could be placed on sustaining agricultural diversity to ensure nutrition quality by supporting small and medium farms, which supply more than 50% of many essential nutrients in the global food supply.[314]

Agriculture is a core determinant of nutrition, and national and global agricultural policies should work to enhance nutrition outcomes.[315] Actions can include providing incentives for primary producers to produce nutritious plant-based foods, focusing investments in agricultural research on identifying pathways for increasing nutrition and sustainability, or developing programmes to support diverse and environmentally sustainable production systems. Because evaluations of the effectiveness of agricultural policies on nutrition and health outcomes can be challenging, more resources need to be directed at developing high-quality evaluations of the effect of upstream policies on nutritional outcomes.[316]

The growing demand for animal source foods puts pressure on land use, increases greenhouse-gas emissions, and, if the animals are grain-fed, are water intensive.[5,6,16,228] However, in some contexts, animal production can also be essential for supporting livelihoods, grassland ecosystem services, poverty alleviation, and benefits of nutritional status (particularly in children and vulnerable populations; panel 3).[317] Therefore, animal production should be considered in specific environmental contexts to determine the extent to which production should decrease, and how sustainable practices (eg, increasing efficiency of feed use[318] and reducing feed-food competition) can support a range of issues, such as animal welfare and antimicrobial resistance. Discussion about what large quantities of food and healthy food means in different contexts is emerging.[319] We support the continuation of this holistic assessment of context-specific trade-offs or win-wins that could arise from animal production.

*Strategy three: sustainably intensify food production, generating high-quality output*

Agricultural practices could be better adapted to soil characteristics, water availability, and climatic drivers of evapotranspiration.[320] For example, in arid regions, drought-tolerant crop varieties can be selected, adequate cropping patterns used, and deficit irrigation (only applied during drought-sensitive growth stages of a crop) and supplemental irrigation (to complement rainfall) applied.[321,322] Local to global scale land-use planning incorporating these considerations can improve sustainability of food production, but complementary measures might also need to be incorporated to ensure these regions have access to a diverse range of nutritious foods (panel 6). In addition, matching production practices to local conditions can increase food production sustainably.[323]

Precision agriculture techniques could be scaled up and subsidised. To obtain high yields of crop per litre of water, it is important to select the right crop cultivar planted at the right density, time, and rotation, and to practice water capture (for increased reliance on green water), soil restoration, and drip irrigation, combined with soil water harvesting and soil conservation practices.[320] These practices will reduce nutrient applications in some countries and increase applications in others. Technologies needed for precision agriculture are expensive, thus private sector companies scale them up for affordability. Governments should provide subsidies to enable their adoption in low-income and middle-income countries.

Practices to prevent nutrient losses from the farm include no or low tillage, using nitrogen-fixing cover crops or crop varieties with large root mass, rotational grazing, and crop residue management or field margin management, such as riparian forests.[324] Further examples include recycling and efficient use of manure and soil erosion control measures (eg, buffer strips to intercept soils and nutrients).[325–327] Additional on-farm measures include covered manure storage, anaerobic digestion for adjustment of nutrient ratios to match crop needs, and biogas production from manure (possibly to power on-farm machinery).[224] Large-scale measures include recycling nitrogen and phosphorus from wastewater systems, cities, agriculture, and industry, and implementing governance mechanisms to ensure regional compliance with water and air quality targets related to formation of reactive nitrogen and nitrogen oxides.

Redistributing fertiliser from over-applying to under-applying regions would increase global food production and improve efficiency of nutrient use and water quality.[184] Increasing nutrient inputs in regions with already high nutrient inputs tends to increase agricultural runoff and reduce efficiency of nutrient use and water quality.[328] In over-applying regions, regulations could be used to mandate water quality targets. For example, after the EU Nitrates Directive was put in place to reduce nitrate concentrations in water, decreases in fertiliser use in the EU have been associated with improved water quality.[329] In under-applying regions, subsidies that increase access to fertiliser can increase yields.[330]

Large increases in carbon sequestration in agricultural soils and above ground are needed[28,208] and can be achieved through various measures. Such measures include incorporating farm organic wastes into soil, low or no tillage, nitrogen-fixing cover plants, replacement of annuals with perennial crops and pastures, agroforestry, establishing buffer strips, and keeping some farmland with natural vegetation. These measures might come at a cost to near-term yields and consequently to farm economy, thus calling for substantial policy support and financial incentives. The 10% conservation in agriculture recommended in Section 3 can, in many contexts, serve multiple roles including carbon capture, nutrient interception, and habitat and corridors for biodiversity (eg, riparian forests).

Biodiversity conservation is essential to maintain ecosystem services that support agriculture. In addition to land-sparing measures, practices that enhance biodiversity within agricultural systems are needed (eg, riparian buffer strips or flower field margins). Presence of natural enemies from increased biodiversity within agricultural systems could prevent yield losses by contributing to integrated weed, pest, and disease management and could increase crop yields via increased pollination by natural pollinators.[331,332] Sparing remaining intact ecosystems is essential to achieving climate and biodiversity boundaries described in Chapter 3. However, sharing space for biodiversity in production landscapes is necessary to secure biodiversity's contribution to food production, including pollination, pest control, carbon capture, and regulating water quality.

*Strategy four: strong and coordinated governance of land and oceans*

Effective governance of land can be achieved by halting expansion of new agricultural land at the expense of natural ecosystems. Direct regulatory measures include strict protections on intact ecosystems, suspending concessions for logging in protected areas, or conversion of remaining intact ecosystems, particularly peatlands and forest areas. Other measures include land-use zoning, regulations prohibiting land clearing, and incentives for protecting natural areas including forests. Approaches that extend beyond the public sector, such as community forest management, can also promote conservation,[333] but their effectiveness varies greatly across contexts.[334,335] Use of private sector approaches (market-based instruments) has increased, but these do not substitute for regulatory governance structures.[336] The boundary of zero net expansion of agricultural land allows for some local expansion in defined contexts. Implementing and enforcing policy mechanisms that ensure that any agricultural expansion occurs in existing managed forests (eg, plantations), abandoned agricultural areas, or other managed ecosystems is particularly important, rather than expanding into natural habitats and other species-rich areas.[144] Conversion within agricultural land is also important, and trade-offs among multiple ecosystem services (eg, potential biodiversity loss or reduction in greenhouse gases, or both, when shifting land uses) need to be considered.[337]

Collective action at local to global levels are needed to stay within the boundary of zero net land use. Coordinated, international governance across national borders is needed to minimise deforestation leakage or harmonise land controls across regions.[338] At the regional and local levels, pairing intensification of sustainable yields with governance and establishment of conservation areas is vital to preventing land-use expansion, conserving biodiversity in production landscapes, and protecting the wellbeing of indigenous communities and shareholders who are dependent on the land (panel 7).[339]

Where appropriate, restoration of degraded land can be promoted through financial incentives for landholders to undertake restoration projects or sanctions for landholders who do not initiate restoration of their land.[340] Active restoration techniques include soil management, planting, or using thinning or burning to speed up vegetation recovery. These approaches have been favoured by decision makers and implementers in the past, yet they are often costly and not always best suited to the area.[341] For example, in tropical forests, natural regeneration is more effective than active restoration at promoting biodiversity and structure of natural vegetation.[341] Policy makers should determine which approach, or what combination of natural and active restoration approaches, are best suited for specific ecological conditions.[341] The global restoration movement could be supported through political commitment to existing frameworks, such as the Bonn Challenge and the Convention on Biological Diversity's Aichi Targets.[342]

Rigorous governance of aquatic ecosystems is fundamental for protecting marine biodiversity as well as ensuring ecosystem functions and continued future supply of wild seafood.[18] The ecosystem approach to fisheries and aquaculture[343,344] should be implemented, implying use of the Code of Conduct for Responsible Fisheries.[345] Harmful subsidies to world fisheries will need to be removed because these lead to over-capacity of the global fishing fleet.[346] In accordance with SDG, number 14, by 2020 at least 10% of marine areas should be closed to fishing. Focus should lie on closure of high seas thus using these areas as a fish bank. This closure can greatly reduce inequality of volume and value distribution of global fisheries and increase net gains of most coastal countries, including the least developed.[347] Other essential measures include general prevention of overfishing and application of the precautionary approach in which absence of scientific information about the effect of a fishery on marine species and ecosystems is not an excuse for delaying crucial action.[348] Moreover, future risks and opportunities related to anticipated aquaculture expansion need to be managed. This management includes implementation of strict regulation on where to locate new operations, antibiotic and chemical use, nutrient runoff, and application of sustainably sourced feed from terrestrial and marine origin. Seafood transparency and eco-certification schemes can also be viable mechanisms for improving performance of the expanding seafood sector.[348]

### *Strategy five: at least halve food loss and waste, in line with global SDGs*

Food loss and waste at initial production stages is highest in low-income and middle-income countries[349] and can be due to poor harvest scheduling and timing, rough or careless handling of produce, or absence of market access. Inadequate cooling and storage facilities can cause farmers to leave crops unharvested or in fields, thus increasing the risk of rotting and contamination. Increased investment in post-harvest infrastructure can help reduce food loss and waste.[350] Investment in processing technologies such as drying and packaging solutions are also needed.

Steep reductions in food loss and waste will require cooperation among multiple actors in the food system to assess sources of food loss and waste and develop targeted solutions. For example, the Save Food Initiative has been used to develop policies, strategies, programmes, and financing strategies for reducing food loss and waste.[351] Infrastructural solutions include initiating collective storage facilities, developing food processing technologies and infrastructure, or investing in cold chains.[352]

Growers can be encouraged to adopt on-farm practices to reduce food loss and waste, such as good animal hygiene (reducing risk of contamination) or improved harvesting and storage techniques. To build this capacity of producers, investment in education, training, and extension services is needed. Because of the high involvement of women in post-harvest handling (as well as many other activities),[353] these services should be designed to engage with and be accessed by women producers in developing countries.

Particularly in highly-developed countries, the public is responsible for a large proportion of food waste.[349] The Commission envisages use of campaigns to promote improved planning of purchases, understanding of best before and use by labels, storage practices, assessment of portions needed, food preparation techniques, and knowledge of how to use leftovers. Appropriate public policy can be one mechanism to achieve these actions. Food loss and waste can be incorporated into national waste policies, food safety policies, food standard rules, food labelling regulations, food redistribution policies, and food subsidies.[352] Financial incentives or

### *Panel 7:* Free trade and food

The role of trade in supporting health and environmental and social development goals is heavily debated.[A44,A45] For example, although some people promote a liberalised environment for international trade to shift nutritious foods and food production inputs from areas of surplus to areas of deficit, others raise concerns about the negative effects on diet-related health. Evidence suggests that the following factors need to be considered to ensure trade policy is enhancing the ability to consume healthy diets from sustainable food systems.

The first factor is natural resource endowment and environmental effects of food production, which vary substantially between regions.[A46,A47] However, some complexities should be considered. Optimising global land use for food production would be challenging because labour and capital are not always easily shifted from producing one food to another.[A45] Providing compensation and social assistance to producers could support these global shifts in patterns of food production.

The second factor is conditions affecting food security. Trade has been promoted as a crucial means of achieving food security by increasing the availability and stability of food supply at affordable prices.[A45,A48–A50] For example, an analysis[A51] found that without liberalised trade, low-income countries might find it particularly difficult to meet their collective macronutrient and micronutrient needs. Increasing employment and income-generating opportunities is also favourable to food security. By contrast, orienting agricultural policy around imports and exports can displace national production and compromise the ability of small-scale farmers and farm labourers in low-income and middle-income countries to produce for local and national markets, thus creating hardship for food-insecure populations.[A52] Evidence indicates that policies that liberalise trade have mixed outcomes. For example, policies have been associated with increased food availability in some countries but not in others.[A53,A54] Likewise for employment and income, trade liberalisation has been associated with increased income and employment opportunities among poorer populations in some countries but not others.[A55] Evidence also suggests that the overall effects on food security depend on the context. For example, in case of emergencies, evidence shows that international trade can mitigate volatility of food prices and increase food security in the event of extreme weather conditions and long-term climactic changes that can disrupt regional crop production.[A56] Whereas, evidence suggests that international trade rules are inadequate at addressing import surges and expose countries to food price volatility.[A57] Therefore, trade policy needs to consider factors affecting food security among its people, and the context in which it is used, to assess how it can be used as a tool to most effectively support food security.

The third factor is the causes of unhealthy diets and diet-related health. Increased open trade policies have made it easier for transnational corporations selling foods associated with unhealthy diets, such as sugary drinks, salty snacks, and fast food, to make their foods available, affordable, and appealing.[A58–60] Trade rules can restrict policy space to implement public health measures designed to improve diets.[A45,A61] The ways in which trade policies affect these outcomes therefore need to be reviewed when considering how trade could most effectively support the goal of healthy diets from sustainable food systems.

International trade is complex. Opportunities to increase coherence between trade policy goals[A62] and actions designed to achieve health and sustainability goals should consider vulnerable populations. Policy makers, public health professionals, nutritionists, environmental scientists, and trade bodies could work together to explore policy objectives that support trade to achieve healthy diets from sustainable food systems.

References cited in this panel can be found in the appendix (pp 28–29).

national waste reduction programmes can encourage collaboration or national innovation competitions among actors to reduce food loss and waste in their supply chains.

## Tools for a Great Food Transformation

Evidence suggests that steps to begin this Great Food Transformation should be taken quickly. Moving towards this transformation requires good data on each country's status of their diet and food system. Diets, effects of their food systems, and particularities of their immediate challenges vary between countries. Opportunities to act inevitably differ across contexts. Despite these varying starting points, common tools that have not been discussed can be used to spur the Great Food Transformation.

Although different priorities and pathways need to be tailored to different contexts, they all need to encourage the global trajectory towards a single set of shared goals. This Commission aimed to set scientific targets for healthy diets and sustainable food production. Gaining consensus on these targets is a first step in urging actors to agree on a common agenda. Targets will then be refined and engaged with at all policy levels.

Because these goals cross-cut political, sectoral, and geographical boundaries, an integrated approach is needed. Integrated approaches can be advanced by establishing formal and frequent interactions between governing groups. For example, UN bodies should facilitate inter-institutional working groups and meetings that focus on cross-sectional issues, such as sustainable diets. The Food and Agriculture Organization, UN Environment Programme, UN Educational, Scientific and Cultural Organization, and UNDP on the Inter-governmental Panel on Ecosystem Services is exploring a specific assessment on food and food systems.

Engineering change across the food system (even if narrowly conceived as economics of supply chain management) is complex enough, but if multi-level, multi-actor, multi-sector, multi-disciplinary change is required, governance faces serious challenges. Because many governments have adopted laissez-faire approaches to consumer choice, the leadership required by governments and food system actors is considerable. This leadership demands coordination, consultation, and good policy facilitation by important policy actors.

Domestic spending will need to increase for policy instruments supporting healthy diets from sustainable food systems. The absence of dedicated funding to support the transformation towards sustainable food systems is a crucial barrier to progress.[354] Investment flows can be leveraged in innovative ways to create multiple wins across the sustainable development challenges. Donors and multi-lateral organisations should be engaged, and reporting processes by the Organisation for Economic Co-operation and Development could be refined to improve tracking of this funding.[311]

Building an alliance of forces that can operationalise the Commission's broad recommendations is challenging. These alliances could include actors at all stages of the food system and operate at all scales so that local actions can be in line with global goals. Such alliances can play a part in bolstering support for the agenda on healthy diets from sustainable food systems and exert influence within and outside of government.

Many annual official or officially approved reports by reputable bodies already exist. Some health-oriented reports might be broadened to include sustainability aspects or, vice versa, environmental or food security reports might include strong nutritional and cultural dimensions. The alternative would be initiating a new annual or bi-annual report on healthy diets from sustainable food systems; methodology for this report would need to be replicable at national and other levels. In addition, monitoring and reporting should go beyond lists of actions and statistics of effects to include regular synthesis and dissemination of lessons learned. Transferable lessons should be spread widely to inspire action.

Expert reports from existing bodies such as UN Environment Programme,[254] UN Committee on World Food Security,[352] and UN Standing Committee on Nutrition have highlighted different aspects of the agenda explored by this Commission.[355] The value of bodies such as the Intergovernmental Panel on Climate Change and the Intergovernmental Panel on Biodiversity and Ecosystem Services is that they constantly champion narrowing the gap between scientific evidence and policy making. These bodies continually collect high-quality data and are subject to intergovernmental agreements, conventions, and Conferences of the Parties. The Great Food Transformation can help to meet existing agreements such as the SDGs, the Paris Agreement, and elements of the WHO-Food and Agriculture Organization Decade of Nutrition Action, but a new Convention or agreement is almost certainly needed. The Commission recommends that international bodies review whether a new oversight body or bodies might be needed, or whether existing bodies could coalesce or have their remit and functions revised to provide necessary focus on healthy diet for all from sustainable food systems (table 7).

## Conclusion

The food we eat and how we produce it will determine the health of people and planet, and major changes must be made to avoid both reduced life expectancy and continued environmental degradation. This Commission presents an

| | Purpose | Tasks 1 | Tasks 2 |
|---|---|---|---|
| Intergovernmental Panel on Climate Change-type mechanism for healthy diets from sustainable food systems | To be a consortium of scientists which collates and updates data for the UN | Provide regular sources of impartial state of the art summaries, which combine data across disciplines | Review policy options for the UN system |
| UN Framework Convention on Sustainable Food Systems | To provide a framework for healthy diets from sustainable food systems with functions akin to those of the Framework Conventions on Climate Change[356] and on Tobacco[357] | Produce guidelines and protocols that set targets and enable monitoring | Host a Food Meeting of the Parties akin to the Convention of the Parties process |
| International Working Party on Sustainable Dietary Guidelines | To produce evidence-based guidelines to add sustainability criteria to existing food-based and nutrient-based dietary guidelines | Provide science-based advice for a wide range of bodies | Set healthy and sustainable dietary guidelines to meet the food-related Sustainable Development Goals |
| A Standing Panel of Experts on healthy diets from sustainable food systems | To be a subcommittee or standing Advisory body to an existing body such as the UN Standing Committee on Nutrition or UN Codex Alimentarius Commission | Produce expert reviews of problem issues for the parent body | Advise national governments on healthy diets from sustainable food systems standards |
| Roadmaps to healthy diets from sustainable food systems | To generate one-off sector plans for public or private sectors or both | Industry-specific and sector-specific plans to contribute to healthy diets from sustainable food systems | Develop plans with phased processes of change to meet specific targets |
| Global Food Systems Report | To author an authoritative annual report, ideally under the auspices of a UN or Bretton Woods body, jointly with others | Produce an annual overview report of the world food system | Conduct special reviews attached to the report |
| Global Food Systems Observatory | Consortium of scientists providing high quality evidence on interventions, modelled on the Cochrane Collaboration and Health/Obesity Observatories | Create a global working network of Universities and scientists to refine evidence-based policy | Monitor regional and national performance in line with agreed targets and criteria |

*Table 7:* **Potential new evidence-based institutions which could champion and monitor the Great Food Transformation**

integrated framework providing quantitative scientific targets for healthy diets and sustainable food production, which together define a safe space within which food systems should operate to ensure that a broad set of human health and environmental sustainability goals are achieved. This framework is universal and provides boundaries that are globally applicable with a high potential of local adaptation and scalability. By defining and quantifying a safe operating space for food systems, diets can be identified that will nurture human health and support environmental sustainability. Our universal healthy reference diet largely consists of vegetables, fruits, whole grains, legumes, nuts, and unsaturated oils, includes a low to moderate amount of seafood and poultry, and includes no or a low quantity of red meat, processed meat, added sugar, refined grains, and starchy vegetables. Our definition of sustainable food production stays within safe planetary boundaries for six environmental processes that together regulate the state of the Earth system, and include climate change, land-system change, freshwater use, biodiversity loss, and interference with the global nitrogen and phosphorus cycles. Applying a global food system modelling framework, we show that it is possible to feed a global population of nearly 10 billion people a healthy diet within food production boundaries by 2050. However, this Great Food Transformation will only be achieved through widespread, multisector, multilevel action that includes a substantial global shift towards healthy dietary patterns, large reductions in food loss and waste, and major improvements in food production practices. Data are sufficient and strong enough to warrant action; delay will increase the likelihood of not achieving the Sustainable Development Goals and the Paris Agreement. This Commission shows that a Great Food Transformation is both necessary and achievable.

**Contributors**

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