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Options for keeping the food system within environmental limits

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The food system is a major driver of climate change, changes in land use, depletion of freshwater resources, and pollution of aquatic and terrestrial ecosystems through excessive nitrogen and phosphorus inputs. Here we show that between 2010 and 2050, as a result of expected changes in population and income levels, the environmental effects of the food system could increase by 50–90% in the absence of technological changes and dedicated mitigation measures, reaching levels that are beyond the planetary boundaries that define a safe operating space for humanity. We analyse several options for reducing the environmental effects of the food system, including dietary changes towards healthier, more plant-based diets, improvements in technologies and management, and reductions in food loss and waste. We find that no single measure is enough to keep these effects within all planetary boundaries simultaneously, and that a synergistic combination of measures will be needed to sufficiently mitigate the projected increase in environmental pressures.

The global food system is a major driver of climate change[1,2], land-use change and biodiversity loss[3,4], depletion of freshwater resources[5,6], and pollution of aquatic and terrestrial ecosystems through nitrogen and phosphorus run-off from fertilizer and manure application[7–9]. It has contributed to the crossing of several of the proposed 'planetary boundaries' that attempt to define a safe operating space for humanity on a stable Earth system[10–12], in particular those concerning climate change, biosphere integrity, and biogeochemical flows related to nitrogen and phosphorous cycles. If socioeconomic changes towards Western consumption patterns continue, the environmental pressures of the food system are likely to intensify[13–16], and humanity might soon approach the planetary boundaries for global freshwater use, change in land use, and ocean acidification[11,12,17]. Beyond those boundaries, ecosystems could be at risk of being destabilized and losing the regulation functions on which populations depend[11,12].

Here we analyse the option space available for the food system to reduce its environmental impacts and stay within the planetary boundaries related to food production. We build on existing analyses that have advanced the planetary-boundary framework in terms of systemic threats to large-scale ecosystems[11,12,18–20], discussed the role of agriculture with respect to those pressures[10,21], and analysed the impacts on individual environmental domains[22,23], including selected measures to alleviate those impacts[22–24]. The planetary-boundary framework is not without criticism, particularly because of the heterogeneity of the different boundaries and their underlying scientific bases, including the difficulty of defining global ecosystem thresholds for local environmental impacts[25–27]. Despite these limitations, we consider the planetary-boundary framework to be useful for framing, in broad terms, the planetary option space that preserves the sustainability of key ecosystems. We acknowledge the ongoing debate by quantifying the planetary boundaries of the food system in terms of broad ranges that reflect methodological uncertainties (see Methods), and by reporting the environmental impacts in absolute terms (for example, emissions in tonnes of carbon dioxide equivalents), which allows for comparisons to other measures of environmental sustainability.

We advance the present state of knowledge by constructing and calibrating a global food-systems model with country-level detail that resolves the major food-related environmental impacts and includes a comprehensive treatment of measures for reducing these impacts (see Methods). The regional detail of the model accounts for different production methods and environmental impacts that are linked by imports and exports of primary, intermediate and final products. We use the food-system model and estimates of present and future food demand to quantify food-related environmental impacts at the country and crop level in 2010 and 2050 for five environmental domains and the related planetary boundaries: greenhouse-gas (GHG) emission related to climate change; cropland use related to land-system change; freshwater use of surface and groundwater; and nitrogen and phosphorus application related to biogeochemical flows.

To characterize pathways towards a food system with lower environmental impacts that stays within planetary boundaries, we connect a region-specific analysis of the food system to a detailed analysis of

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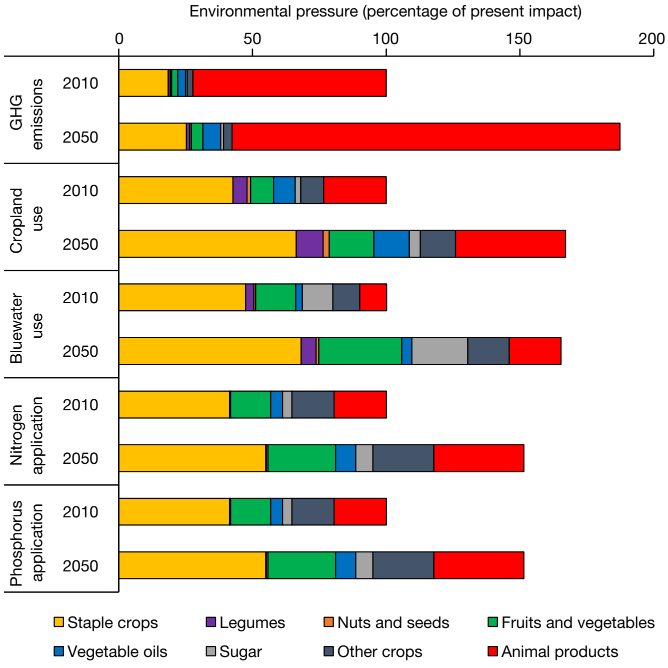

Fig. 1 | Present (2010) and projected (2050) environmental pressures on five environmental domains divided by food group. Environmental pressures are allocated to the final food product, accounting for the use and impacts of primary products in the production of vegetable oils and refined sugar, and for feed requirements in animal products. Impacts are shown as percentages of present impacts, given a baseline projection to 2050 without dedicated mitigation measures for a middle-of-the-road socioeconomic development pathway (SSP2). Absolute impacts for all socioeconomic pathways are provided in the main text and the data referred to in the 'Data availability' statement (see Methods).

measures of change, including reductions in food loss and waste, technological and management-related improvements, and dietary changes towards healthier, more plant-based diets (Extended Data Table 1). The scenarios regarding food loss and waste align with and exceed commitments made as part of the United Nations' Sustainable Development Goals[28–30]. The scenarios concerning technological change account for future improvements in agricultural yields and fertilizer application, increases in feed efficiency, and changes in management practices[31–34]. Finally, the scenarios around dietary change include changes towards dietary guidelines and more plant-based dietary patterns that are in line with present evidence on healthy eating[35–37].

In our baseline trajectory, we account for different socioeconomic pathways of population and income growth[33], and project future demand for environmental resources in the absence of technological changes and dedicated mitigation measures. Although some of the measures of change considered here can be expected to be implemented by 2050, their level of ambition is uncertain and implementation will not happen automatically. We therefore analyse each measure of change explicitly and differentiate between two degrees of implementation: medium and high ambition. Measures of medium ambition are in line with stated intentions (for example, reducing food loss and waste by half), and measures of high ambition go beyond expectations but can be considered attainable with large-scale adoption of existing best practices (for example, reducing food loss and waste by 75%).

Environmental impacts of the food system

Our analysis indicates that current and projected levels of agricultural production, in the absence of targeted mitigation measures, will greatly affect the Earth's environment. We estimate that, in 2010, the food system emitted roughly the equivalent of 5.2 billion tonnes of carbon dioxide in GHG emissions in the form of methane and nitrous oxide; the food system also occupied 12.6 million km^2 of cropland, used 1,810 km^3 of freshwater resources from surface and groundwater (bluewater), and applied 104 teragrams of nitrogen (TgN) and 18 teragrams of phosphorus (TgP) in the form of fertilizers (see Methods, 'Data availability'). Our estimates are comparable to previous estimates of food-related GHG emissions[1,38] of 4.6–5.8 billion tonnes of carbon dioxide equivalents, global cropland use[39] of 12.2–17.1 million km^2 in 2000, bluewater use[5,20] in 2000 of 1,700–2,270 km^3, and nitrogen[40] and phosphorus[40,41] application in 2010 of 104 TgN and 15.8–18.8 TgP.

Food production and consumption are projected to change between 2010 and 2050 (Extended Data Table 2) as a result of expected socioeconomic developments (Supplementary Table 1). Those developments include the growth of the global population by about a third (with a range of 23–45%, from 6.9 billion in 2010 to 8.5–10 billion in 2050) and a tripling of global income (with a range of 2.6–4.2, from US$68 trillion in 2010 to US$180–290 trillion in 2050)[33]. Because of these changes, we predict the environmental pressures of the food system to increase by 50–92% for each indicator in the absence of technological change and other mitigation measures (Fig. 1). The greatest increases along this baseline pathway are projected for GHG emissions (87%, range 80–92%), then for the demand for cropland use (67%, range 66–68%), bluewater use (65%, range 64–65%), phosphorus application (54%, range 51–55%) and nitrogen application (51%, range 50–52%).

Specific food groups vary in their environmental impacts (Fig. 1). The production of animal products generates the majority of food-related GHG emissions (72–78% of total agricultural emissions), which is due to low feed-conversion efficiencies, enteric fermentation in ruminants, and manure-related emissions[42]; the feed-related impacts of animal products also contribute to bluewater use (around 10%) and pressures on cropland, as well as nitrogen and phosphorus application (20–25% each). By comparison, staple crops have generally lower environmental footprints (impacts per kg of product) than animal products (Extended Data Table 3), in particular for GHG emissions, but they can have high total impacts because of their higher production volumes (Extended Data Table 2). According to our estimates, staple crops grown for human consumption are responsible for a third to a half (30–50%) of cropland use, bluewater use, and nitrogen and phosphorus application. The projected population growth between 2010 and 2050 contributes to a general increase in the impacts of each food group, and the projected income growth changes the relative contribution of each, with a shift towards a larger proportion of impacts from animal products (7–16% increase across environmental domains) and fruits and vegetables (2–28% increase), and a smaller proportion from staple crops (7–19% reduction).

Changes in food management, technology and diets

Reducing food loss and waste is one measure for reducing food demand and the associated environmental impacts. At present it is estimated that more than a third of all food that is produced is lost before it reaches the market, or is wasted by households[28]. For our analysis, we evaluated the impacts of reducing food loss and waste to one half—a value in line with pledges made as part of the Sustainable Development Goals[29]—and we also considered a reduction in food loss and waste by 75%, which is probably close to the maximum theoretically avoidable value[30]. We estimate that halving food loss and waste would reduce environmental pressures by 6–16% compared with the baseline projection for 2050, and that reducing food loss and waste by 75% would reduce environmental pressures by 9–24% (Fig. 2). Relatively more staple crops and fruits and vegetables are wasted than animal products[28], which explains why the impacts of changes in food loss and waste are smaller for the livestock-dominated domains, such as GHG emissions, than for the staple-crop-dominated ones, such as cropland and bluewater use and nitrogen and phosphorus application.

Technological changes increase the efficiency of production and reduce the environmental impact per unit of food produced. We analysed the most commonly considered technological advances and changes in management practices with respect to their environmental impacts (Extended Data Table 1). The measures include: increases

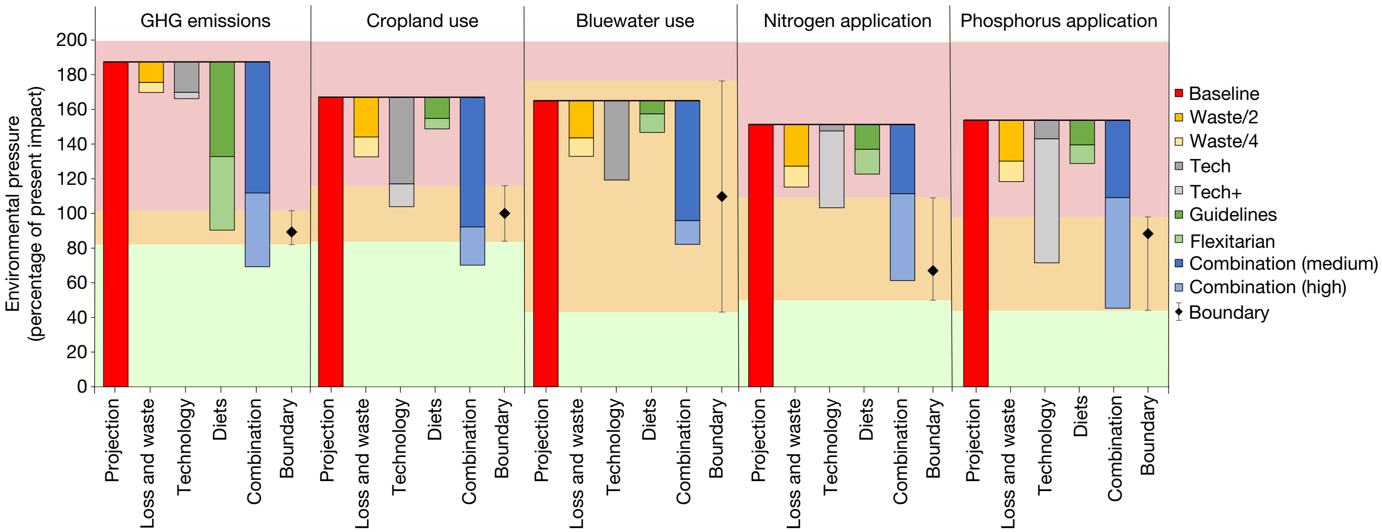

Fig. 2 | Impacts of reductions in food loss and waste, technological change, and dietary changes on global environmental pressures in 2050. These projections of environmental pressures in 2050 are baseline projections without dedicated mitigation measures for a middle-of-the-road development pathway, and are expressed as percentages of present impacts (see Fig. 1). The different measures of change and their combination are depicted as reductions from the baseline projections for the different environmental domains (for example, the 'diets' bar that ends at 90% of present impacts of GHG emissions indicates that ambitious dietary changes (flexitarian) can reduce the projected increase of GHG emissions from 187% of present impacts to 90%, which represents a reduction of 52% or 97 percentage points; and dietary changes of medium ambition (guidelines), which in the figure end at the split line of the 'diets' bar, can reduce GHG emissions from 187% of present impacts to 133%, which represents a reduction of 29% or 54 percentage points). The loss and waste scenarios include reducing food loss and waste by half (waste/2) and by 75% (waste/4). The technology scenarios include medium-ambition technological changes up to 2050 (tech) and more ambitious technological changes (tech+). The diet scenarios include diets aligned with global dietary guidelines (guidelines), and more plant-based flexitarian diets (flexitarian) that are reflective of present evidence on healthy eating. The scenario combinations include all measures of medium ambition (comb(med): waste/2, tech, guidelines) and all measures of high ambition (comb(high): waste/4, tech+, flexitarian), the latter including an optimistic socioeconomic development pathway with higher income and lower population growth. The diamonds indicate mean planetary-boundary values (boundary), each associated with uncertainty intervals highlighted by colour (light green, below the mean value; light orange, between minimum and maximum values; light red, above maximum values).

in agricultural yields, which reduce the demand for additional cropland[32,33]; rebalancing of fertilizer application between overapplying and underapplying regions[32], as well as increasing nitrogen-use efficiency[34,43] and phosphorus recycling[7], which reduce demand for additional nitrogen and phosphorus inputs; improvements in water management that increase basin efficiency, storage capacity, and better utilization of rainwater[33]; and agricultural mitigation options, including changes in irrigation, cropping and fertilization that reduce methane and nitrous oxide emissions from rice and other crops, and changes in manure management, feed conversion and feed additives that reduce enteric fermentation in livestock[31]. We estimate that implementing these measures could reduce the environmental pressures of the food system by 3–30% compared with the 2050 baseline projection in medium-ambition scenarios, and by 11–54% in high-ambition scenarios (Fig. 2). In each case, the higher-end estimates are for the staple-crop-dominated environmental indicators (cropland and bluewater use, and nitrogen and phosphorus application), for which general improvements in water management, agricultural yields, phosphorus-recycling rates and nitrogen-use efficiencies are particularly effective. The lower-end estimates are for GHG emissions, for which the contribution from livestock-related emissions is, to a large extent, an inherent characteristic of the animals and therefore cannot be reduced more substantially through existing mitigation options[31,44] (Extended Data Table 4).

Dietary changes towards healthier diets can reduce the environmental impacts of the food system when environmentally intensive foods, in particular animal products, are replaced by less intensive food types[15,16]. For our analysis, we analysed dietary changes towards diets in line with global dietary guidelines for the consumption of red meat, sugar, fruits and vegetables, and total energy intake[35,36]; as well as to more plant-based (flexitarian) diets that more comprehensively reflect the current evidence on healthy eating[37,45] by including lower amounts of red and other meats and greater amounts of fruits, vegetables, nuts and legumes (Extended Data Tables 1 and 5). We estimate that, compared with the baseline projection for 2050, dietary changes towards healthier diets could reduce GHG emissions and other environmental impacts by 29% and 5–9%, respectively, for the dietary-guidelines scenario, and by 56% and 6–22%, respectively, for the more plant-based diet scenario (Fig. 2). The changes are in line with the dietary composition of the diets and the environmental footprints of each food group (Fig. 1, Extended Data Table 1 and Supplementary Table 2). Changes in meat consumption dominate the impacts on GHG emissions, while for the other domains the environmental pressures associated with greater consumption of fruits, vegetables, nuts and legumes are more important but outweighed by the environmental benefits associated with lower consumption of meat, staple crops and sugar, and a generally lower energy intake in line with healthy body weights and recommended levels of physical activity[35] (Extended Data Table 6).

To understand how the combined implementation of some or all of the discussed measures could influence the environmental pressures of the food system, we constructed an environmental option space by combining all measures of medium ambition and all measures of high ambition. Our analysis indicates that much of the increase in environmental pressures that is expected to occur by 2050 could be mitigated if measures were combined (Fig. 2). Combining all measures of medium ambition could reduce environmental pressures by around 25–45% compared with the baseline projection for 2050, resulting in total environmental impacts that are within 15% above and below present impacts. Combining all measures of high ambition could deliver reductions of 30–60%, resulting in environmental impacts that are 20–55% less than the current ones. In line with the differentiated impacts of the different measures of change, dietary change contributes the most to the reductions in GHG emissions, and technological and management-related changes contribute the most to reductions in the other environmental impacts, while reductions in food loss and waste contribute up to a third to the overall reductions (Extended Data Fig. 1).

Diet scenario	Tech scenario	Loss and waste scenario	GHG emissions			Cropland use			Bluewater use			Nitrogen application			Phosphorus application		
			SSP2	SSP1	SSP3	SSP2	SSP1	SSP3	SSP2	SSP1	SSP3	SSP2	SSP1	SSP3	SSP2	SSP1	SSP3
Baseline	Baseline	Baseline	4	4	4	4	4	4	3	3	3	4	4	4	4	4	4
		Waste/2	4	4	4	4	4	4	3	3	3	4	4	4	4	4	4
		Waste/4	4	4	4	4	4	4	3	3	3	4	4	4	4	4	4
	Tech	Baseline	4	4	4	4	4	4	3	3	3	4	4	4	4	4	4
		Waste/2	4	4	4	3	3	3	2	2	2	4	4	4	4	4	4
		Waste/4	4	4	4	2	2	2	2	2	2	4	4	4	4	4	4
	Tech+	Baseline	4	4	4	3	3	3	3	3	3	3	3	3	2	2	2
		Waste/2	4	4	4	2	2	2	2	2	2	3	3	3	2	2	2
		Waste/4	4	4	4	1	1	1	2	2	2	3	3	3	2	2	2
Guidelines	Baseline	Baseline	4	4	4	4	4	4	3	3	3	4	4	4	4	4	4
		Waste/2	4	4	4	4	4	4	3	3	3	4	4	4	4	4	4
		Waste/4	4	4	4	4	3	4	3	3	3	3	3	3	4	4	4
	Tech	Baseline	4	4	4	3	3	3	3	2	3	4	4	4	4	4	4
		Waste/2	4	4	4	2	2	2	2	2	2	4	3	4	4	4	4
		Waste/4	4	4	4	2	1	2	2	2	2	3	3	3	4	3	4
	Tech+	Baseline	4	4	4	2	2	2	3	2	3	3	3	3	2	2	2
		Waste/2	4	4	4	1	1	1	2	2	2	3	3	3	2	2	2
		Waste/4	4	3	4	1	1	1	2	2	2	3	3	3	2	2	2
Flexitarian	Baseline	Baseline	3	2	3	4	4	4	3	3	3	4	4	4	4	4	4
		Waste/2	1	1	2	4	4	4	3	3	3	3	3	3	4	4	4
		Waste/4	1	1	1	4	3	4	3	2	3	3	3	3	3	3	3
	Tech	Baseline	2	1	2	3	3	3	2	2	3	4	4	4	4	4	4
		Waste/2	1	1	1	2	2	2	2	2	2	3	3	3	4	4	4
		Waste/4	1	1	1	1	1	2	2	2	2	3	3	3	3	2	3
	Tech+	Baseline	1	1	2	2	2	2	2	2	3	3	3	3	2	2	2
		Waste/2	1	1	1	1	1	1	2	2	2	3	2	3	2	2	2
		Waste/4	1	1	1	1	1	1	2	2	2	2	2	2	2	1	2

Fig. 3 | Planetary option space. The figure shows combinations of dietary change, technological change (tech or tech+), changes in food loss and waste (waste/2 or waste/4), and socioeconomic development pathways (SSP1, SSP2 or SSP3). These changes are applied to baseline conditions in 2050 (baseline). The diet scenarios include diets aligned with global dietary guidelines (guidelines), and more plant-based flexitarian diets (flexitarian) that are reflective of the current evidence on healthy eating. The loss and waste scenarios include reducing food loss and waste by half (waste/2) and by 75% (waste/4). The technology scenarios include medium-ambition technological changes up to 2050 (tech) and more ambitious technological changes (tech+). The socioeconomic development pathways include a middle-of-the-road development pathway (SSP2), a more optimistic one with higher income and lower population growth (SSP1), and a more pessimistic one with lower income and higher population growth (SSP3). Colours and numbers indicate combinations that are below the lower bound of the planetary-boundary range (dark green, 1), below the mean value but above the minimum value (light green, 2), above the mean value but below the maximum (orange, 3), and above the maximum value (red, 4).

Planetary option space

What level of reduction in environmental pressures should be aimed for? We can explore this question through comparison to the associated planetary boundaries that are intended to describe a safe operating space for humanity. For our analysis, we adapted or newly quantified the food-related planetary-boundary values, including upper and lower limits (Extended Data Table 7, Extended Data Fig. 2 and Methods). According to our quantification, the planetary boundaries define a space around the present values for most environmental domains, with a mean value slightly below present values for food-related GHG emissions, at current values for cropland use, slightly above present values for bluewater use, and substantially below present values for nitrogen and phosphorus application (Fig. 2). Following the baseline trajectory of population and income change, and the related changes in food consumption and production, would lead to all mean values of the planetary boundaries being crossed. The environmental impacts of the food system would exceed the planetary boundaries for food-related GHG emissions by 110%, for cropland use by 70%, for bluewater use by 50%, for nitrogen application by 125%, and for phosphorus application by 75%.

Our analysis indicates that staying within planetary boundaries is possible with a combination of measures of high ambition for GHG emissions and nitrogen and phosphorus application, and with a combination of measures of medium ambition for cropland and bluewater use (Fig. 2). An analysis of the planetary option space details the possible combination of measures (Fig. 3). It shows that staying within the mean value of the GHG boundary requires ambitious dietary change towards more plant-based, flexitarian diets, in combination with either reductions in food loss and waste or technological improvements; staying within the mean values of the cropland and bluewater boundaries requires technological improvements in combination with reductions in food loss and waste; and staying within the mean values of the nitrogen and phosphorus boundaries requires ambitious technological improvements combined (for the nitrogen boundary) with dietary changes towards more plant-based diets, reductions in food loss and waste, and, in some combinations, a more optimistic socioeconomic development pathway that includes lower population and higher income growth than is expected at present. Combining those measures synergistically results in adoption of different measures of technological change for each environmental domain, coupled in each case to dietary changes towards more plant-based diets, reductions in food loss and waste, and an optimistic socioeconomic development pathway (Fig. 4).

Uncertainties

Our estimates are subject to several uncertainties. Some of the planetary-boundary values have a large uncertainty range, which reflects the difficulties of scaling up local environmental pressures to global levels[12,20], in particular regarding bluewater use and nitrogen and phosphorus application (see Methods). The planetary-boundary framework can therefore provide only a very broad measure of the sustainability of the food system. Our analysis indicates that using the upper bound of the planetary-boundary range increases the option space (Fig. 3) and, for example, does not require reductions in food loss and waste or a more optimistic socioeconomic development pathway; however, meeting the lower bound of the planetary-boundary range would

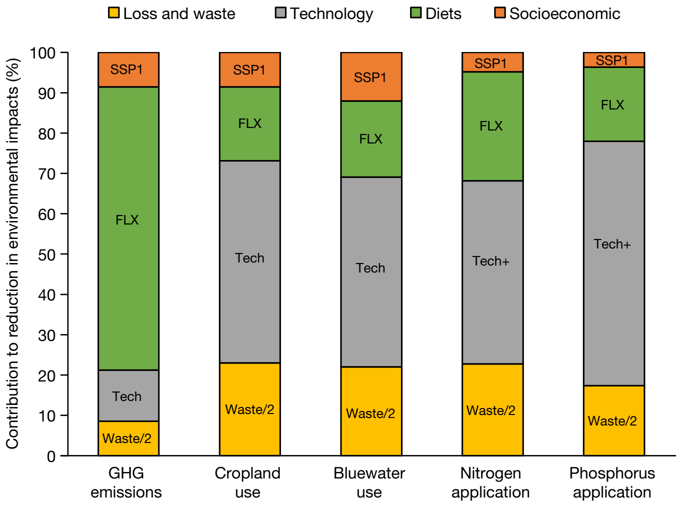

Fig. 4 | Combination and relative contributions of mitigation measures that simultaneously reduce environmental impacts below the mean values of the planetary-boundary range. The mitigation measures include different levels of technological improvements for each environmental domain (measures of high ambition (tech+) for nitrogen and phosphorus application, and measures of medium ambition (tech) for GHG emissions and for cropland and bluewater use). The other measures are not differentiated by environmental domain, and include a halving of food loss and waste (waste/2), changes towards more plant-based flexitarian diets (FLX), and optimistic socioeconomic development with higher income and lower population growth (SSP1) than expected at present. A middle-of-the-road development pathway is also feasible when combined with more ambitious reductions in food loss and waste (see Fig. 3).

not be possible for bluewater use and nitrogen application with the mitigation options considered here. Using different control variables to measure the state of planetary boundaries could also affect the option space. However, assessing the impacts of nitrogen pollution by using a measure of nitrogen surplus that accounts for all inputs and offtakes of nitrogen had little influence on the option space (Extended Data Fig. 3).

Other uncertainties are related to the set-up of our modelling framework. Although we did consider some feedback effects between the different measures of change—particularly between changes in yields and the demand for bluewater, nitrogen and phosphorus use—this was limited to the scenarios of medium ambition (see Methods). This method allowed for the differentiated adoption of ambitious technological change for domains other than cropland use without also requiring such levels for the latter. In a sensitivity analysis, we assessed the feedback effects that very high yield increases could have on nitrogen and phosphorus application[32], and found that the demand for nitrogen and phosphorus could increase across the different scenario combinations with large yield-gap closures by 8–14% and 25–32%, respectively, which would moderately reduce the planetary option space for those scenarios (Extended Data Fig. 3). In line with our focus on mitigation measures, we did not assess the impacts that climate change could have on crop yields and freshwater availability[46]. While economic responses might be able to mitigate some proportion of the biophysical impacts of climate change[47], such responses could reduce the availability and effectiveness of additional mitigation and adaptation measures, and thereby reduce the planetary option space.

Additional research would reduce the uncertainty of our scenario analysis. In our scenarios of change, we chose to focus on changes—technological, dietary, and in food loss and waste—that are considered realistic or attainable, or have been set as goals. This means that we did not include technologies or mitigation measures that have large uncertainties at present, such as soil carbon sequestration, nitrogen-fixing cereals, or landless biomass production. Some of those measures have shown some prospect in certain regions, but it is not yet clear whether they are scalable and what their relationship to existing technologies and environmental targets would be[48]. For example, land-based carbon sequestration, while reducing GHG emissions, could put additional pressures on croplands or pastures, with implications for land-use and biodiversity targets. Other areas for further research include the quantification of co-benefits of food-system change, for example, on health[15,49], biodiversity[50], and the economy[47], as well as context-specific metrics of sustainability and a greater focus on livelihood, for example in terms of food security[51].

Policy implications

Our analysis suggests that staying within the planetary boundaries of the food system requires a combination of measures: GHG emissions cannot be sufficiently mitigated without dietary changes towards more plant-based diets; cropland and bluewater use are best addressed by improvements in technologies and management that close yield gaps and increase water-use efficiency; and reducing nitrogen and phosphorus application will require a combination of measures to stay below the mean values of the planetary boundaries, including dietary change, reductions in food loss and waste, improvements in technologies and management that increase use efficiencies for nitrogen and recycling rates for phosphorus, and efforts in global socioeconomic development.

Implementation of these measures will depend on the regulatory and incentive framework in each region. In particular, practical options exist for improving technologies and management practices (Extended Data Table 1), but adoption of those options will require investment in public infrastructure, the right incentive schemes for farmers (including support mechanisms to adopt best available practices), and better regulation (for example, of water use and quality). Concrete options also exist for improving socioeconomic development in developing countries, including investments in education, particularly for women, and improving access to general and reproductive health services[52]. Meaningfully reducing food loss and waste will require measures across the entire food-supply chain[30], with possible emphasis on investments in agricultural infrastructure, technological skills, storage, transport, and distribution in developing regions; and education and awareness campaigns, food labelling, improved packaging that prolongs shelf life, and changes in legislation and business behaviour that promote closed-loop supply chains (in which waste is recycled back into the system) in developed areas. For dietary change, the available evidence suggests that providing information without additional economic or environmental changes has a limited influence on behaviour, and that integrated, multicomponent approaches that include clear policy measures might be best suited for changing diets[53,54]. Those can include a combination of media and education campaigns; labelling and consumer information; fiscal measures, such as taxation, subsidies, and other economic incentives; school and workplace approaches; local environmental changes; and direct restriction and mandates[54]. An important first step would be to align national food-based dietary guidelines with the present evidence on healthy eating and the environmental impacts of diets[55,56].

Our analysis suggests that the environmental impacts of the food system could increase markedly owing to expected changes in food consumption and production, and, in the absence of targeted measures, would exceed planetary boundaries to the extent that key ecosystem processes could become at risk of being destabilized. Synergistically combining improvements in technologies and management, reductions in food loss and waste, and dietary changes towards healthier, more plant-based diets, with particular attention to local contexts and environmental pressures, will be a key challenge in defining region-specific pathways for the sustainable development of food systems within the planetary option space. We hope that the country-specific data and suite of scenarios produced for this study (see Methods, 'Data availability') can provide a good starting point for this endeavour.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of data availability and associated accession codes are available at https://doi.org/10.1038/s41586-018-0594-0.

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the analysis of nitrogen and phosphorus. S.J.V., M.H. and K.M.C. contributed data for the analysis of GHG emissions. M.J. and M.T. contributed data for the analysis of fish and seafood. W.W. designed the flexitarian diet and contributed to the discussion on the health aspects of dietary change. F.D. contributed to the discussion on the planetary boundary related to land use. L.J.G. and R.Z. contributed to the discussion on water use. P.S. and M.R. contributed to discussion on the health aspects of dietary change. B.L. facilitated discussions and contributed to the discussion on the planetary boundaries related to the food system. J.F. contributed to the discussion and background of the study. J.R., H.C.J.G. and D.T. contributed to discussion on the planetary boundaries related to the food system. All authors commented on the manuscript draft and approved the submission.

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METHODS

Food-system model. For our analysis, we constructed a food-systems model that connects food consumption and production across regions (Supplementary Information). We distinguished several steps along the food chain: primary production (including non-food uses, for example, in industry, seed banks, and as biofuels); trade in primary commodities; processing to oils, oil cakes and refined sugar; use of feed for animals; and trade in processed commodities and animals (Extended Data Table 2). We parameterized the model with data from the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT)[33] on current and future food production, processing factors, and feed requirements for 62 agricultural commodities and 159 countries. Projections of future food consumption and production were based on statistical association with changes in income and population, and were in line with other projections[57].

To assess the environmental impacts of the food system, we paired the food-system model with a set of country-specific environmental footprints related to GHG emissions, cropland use, bluewater use, and nitrogen and phosphorus application (Extended Data Table 3; data available upon request). In line with projections of the allowable agricultural emissions budget[58], and our separate treatment of land use, we focused on the non-CO_2 emissions of agriculture, in particular methane and nitrous oxide. Data on GHG emissions were adopted from country-specific analyses of GHG emissions from crops[59] and livestock[38]. Non-CO_2 emissions of fish and seafood were calculated on the basis of feed requirements and feed-related emissions of aquaculture[60], and on projections of the ratio between wild-caught and farmed fish production[61,62]. Our baseline emissions estimate agrees well with existing ones that follow the same methodology[1,63].

Data on cropland and consumptive bluewater use were adopted from the IMPACT model[33]. To derive commodity-specific footprints, we divided use data by data on primary production, and we calculated the footprints of processed goods (vegetable oils, refined sugar) by using country-specific conversion ratios[33], and splitting co-products (oils and oil meals) by economic value to avoid double counting. We used country-specific feed requirements for terrestrial animals[33] to derive the cropland and bluewater footprints for meat and dairy, and we used global feed requirements for aquaculture[60] and projections of the ratio between wild-caught and farmed fish production[61,62] to derive the cropland and bluewater footprints for fish and seafood.

Data on fertilizer application rates of nitrogen and phosphorous were adopted from the International Fertilizer Industry Association[40]. In line with the planetary boundaries, we focus on application rates as the control variables in our main analysis. However, we note that regional environmental impacts often depend on the surplus of reactive nitrogen, a measure that accounts for all inputs and offtakes of nitrogen[64]. For a sensitivity analysis, we therefore constructed a region-specific nitrogen-budget module and linked it to the food-system model. Therein, we define the nitrogen surplus as the sum of fertilizer use, fixation by crops, manure application, human excreta and atmospheric deposition, minus nitrogen offtake by crops[22,43,65] (Supplementary Information). The results of the sensitivity analysis are reported in Extended Data Fig. 3.

Scenario analysis. We used the food-system model to estimate the environmental impacts of the food system in 2050 on GHG emissions, cropland use, bluewater use, and nitrogen and phosphorus application. To estimate the environmental impacts in the absence of dedicated mitigation measures (a scenario we term 'baseline projection'), we paired the footprints of current intensity to future projections of food demand along several socioeconomic pathways that were developed by the climate-change research community (Supplementary Table 1), including a middle-of-the-road development pathway (SSP2), a more optimistic pathway with higher income and lower population growth (SSP1), and a more pessimistic pathway with lower income and greater population growth (SSP3)[66–68]. Underlying the pathways are data and projections of the age, sex and educational structure of populations, as well as age-specific fertility, mortality and migration[67].

We then analysed the option space for reducing the environmental pressures of the food system by constructing scenarios of changes in food loss and waste, technological change and dietary change (Extended Data Table 1). For each measure, we differentiated between changes of medium and high ambition. Estimates of food loss and waste were based on percentage values reported by the UN Food and Agriculture Organization (FAO)[28]. In the standard scenario (waste/2), we assumed that food losses at the production side and food waste at the consumption side are reduced by half—a goal in line with the UN Sustainable Development Goals for 2030. In the ambitious scenarios (waste/4), we assumed reductions in food loss and waste of 75%, which is probably close to the maximum value that can be theoretically avoided[30].

The scenarios of technological change (tech and tech+) include projected efficiency gains in emissions intensities, agricultural yields, feed conversion, water use, and nitrogen and phosphorus application (Extended Data Table 4). For the scenarios describing changes in emissions intensities of foods, we incorporated the mitigation potential of bottom-up changes in management practices and technologies by using marginal abatement cost curves[31] and the value of the social cost of carbon (SCC) in 2050[69]. The mitigation options included changes in irrigation, cropping and fertilization 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. We used SCC values of 72 US dollars per metric ton of CO_2 equivalents (US\$/tCO_2 equivalents) associated with a rate of discounting future climate damages by 3% for the scenario of medium ambition (tech), and implemented all available mitigation options (equivalent to using a SCC of above 99 US\$/tCO_2 equivalents) for the scenario of high ambition (tech+). No marginal abatement curves were available for some crops, such as fruits, vegetables, nuts, sugar crops and oilseeds. Adopting the average mitigation potential for staple crops for these crops would increase the total mitigation potential by 1%.

Efficiency gains in agricultural yields, water management and feed conversion were based on IMPACT projections[33]. For water management, we relied on an integrated hydrological model within IMPACT that operates at the level of watersheds and accounts for management changes that increase basin efficiency, storage capacity and better utilization of rainwater[33]. For most crops, improvements in water management exceed increased water demand associated with yield improvements, except for soybeans. For agricultural yields, the gains in land-use efficiency matched estimates of yield-gap closures of about 75% between present yields and yields that are feasible in a given agricultural-climatic zone[32]. The potential efficiency gains in nitrogen and phosphorus application rates included rebalancing of fertilizer application rates between overapplying and underapplying regions in line with closing yield gaps[32]. In the ambitious technology scenario (tech+), we increased yield-gap closures to 90% on the basis of data from a previous study[32], and assumed additional improvements in nitrogen-use efficiency of 30% (in line with targets suggested by the Global Nitrogen Assessment[34]) and a recycling rate of phosphorus[7] of 50%. No further changes in efficiency were assumed for water use in the tech+ scenario. For most crops, land-use efficiencies increase in the ambitious technology scenario, except in the case of soybeans, which are assessed on a more conservative basis in a previous study[32] than by the IMPACT team.

The scenarios of dietary change include shifts towards diets that are in line with global dietary guidelines (guidelines), and towards dietary patterns that are more specialized but nutritionally balanced (flexitarian). For the former, we followed suggestions to limit the intake of red meat to less than 300 g per week[70] and the intake of added sugar to less than 5% of total energy intake (about 31 g per day)[71], to consume five portions (400 grams per day) or more of fruits and vegetables[36], and to balance energy intake (and physical activity levels) to maintain a healthy body weight[35]. Estimates of energy intake were based on the calorie needs of a moderately active population of US characteristics for height, divided into five-year age groups[72]—something that can be seen as an upper bound. Calorie needs reach a maximum of 2,500 kcal per day for ages 19–25 (averaged between men and women), but are reduced to 2,000 kcal per day for ages 66 and older. The average calorie needs differed by region according to its age composition, and averaged around 2,100 kcal per day. In a sensitivity analysis, we implemented changes in dietary composition only, without restricting energy intake. Baseline intakes of food and energy were calculated from food-availability projections of the IMPACT model by using region-specific factors of food waste and ratios of the edible portions of foods[28].

In scenarios of ambitious dietary change, we increased the stringency of the global recommendations and defined more plant-based (flexitarian) dietary patterns that reflect current evidence on healthy eating[37,46,73] (Extended Data Table 5 and Supplementary Table 2). The flexitarian diets included: at least 500 g per day of fruits and vegetables of different colours and groups (the composition of which is determined by regional preferences); at least 100 g per day of plant-based protein sources (legumes, soybeans and nuts); modest amounts of animal-based proteins, such as poultry, fish, milk and eggs; and limited amounts of red meat (one portion per week), refined sugar (less than 5% of total energy), vegetable oils that are high in saturated fat (in particular palm oil) and starchy foods with a relatively high glycaemic index. We aimed to preserve the regional character of dietary patterns by maintaining the regional composition of specific foods within broader categories, such as preferences for specific staple crops (wheat, maize, rice and so on) and fruits (temperate or tropical).

Planetary boundaries. The planetary-boundary framework attempts to define a safe operating space for humanity that is characterized by a stable Earth system[10–12]. Above planetary boundaries, it is suggested that ecosystem processes are at risk of becoming destabilized[11,12]. To contextualize the environmental impacts of the food system, we critically reviewed and adapted planetary-boundary values for GHG emissions, cropland use, bluewater use, and nitrogen and phosphorus application (Extended Data Table 7). For the climate-change boundary, we adopted an emissions budget for food-related (non-CO_2) GHG emissions that is in line with having a 66% chance of limiting global warming to below 2 °C (Representative Concentration Pathway (RCP)2.6); we derived this budget from a model comparison of three integrated assessment models[58], normalized to the marker scenario of the associated emissions pathway[63]. The resulting budget of 4.7 $GtCO_2$ equivalents (range 4.3–5.3 $GtCO_2$ equivalents). focuses on the non-CO_2 emissions related to agriculture (methane and nitrous oxide), in line with previous assessments[58] and methodology followed by the International Panel on Climate Change. However, we note that agriculture and land use also act as source and sink for CO_2, for example through deforestation and carbon sequestration in soils[74]. How those flows should be balanced vis-à-vis the emissions from other sectors, and how additional pressures from land-based CO_2 sequestration contribute or counteract other sustainability targets and planetary boundaries, are important questions for future research.

Large uncertainties exist as to what an appropriate planetary boundary for land use should be[12]. From an analysis of forest biomes, a boundary value[12] was previously suggested in line with maintaining (not increasing pressure on) present forest cover. Such a target is in line with the strongly correlated target for biosphere integrity if nonagricultural land is placed under protection of biodiversity-compatible land use[12,75,76]. Because our modelling framework explicitly tracks cropland use, we translate the suggested target to a value of keeping current cropland use at 12.6 million km^2 (range 10.6–14.6 million km^2), given our own model calculations using the IMPACT model[33]. In future work, it will be desirable to include the role of pastures, an explicit treatment of forest cover, and further differentiation of other forms of land cover. However, a complication with switching from land use to forest cover is that the latter depends not only on agriculture, but also on wood harvesting, urbanization, and other socioeconomic variables. More than two-thirds of agricultural land is used for grazing. Converting highly productive grazing land into cropland could therefore be a conservation strategy that would relax the boundary value for cropland without affecting forest cover. However, estimates of feasible conversion ratios are still a matter of debate[23].

Two basin-level assessments of the environmental flow requirements of river systems have been used to suggest planetary boundaries for the consumption of bluewater[12,20]. We adopt the more stringent values of the more detailed standalone analysis (2,800 km^3; range 1,100–4,500 km^3)[20], which includes the other suggested values in its uncertainty range[12,77]. Because not all bluewater is used in agriculture, we scale from total consumptive bluewater use (2,550 km^3)[5] to the consumptive bluewater used in agriculture (1,810 km^3) as assessed with our hydrological model[33], which yields a boundary of 1,980 km^3 (range 780–3,190 km^3) of bluewater used in agriculture. We note that uncertainties persist about the concrete assumptions on environmental flow requirements[12,78], and about which methodology would be best suited[79].

To inform the boundary value for reactive nitrogen, a previous study[19] calculated global risk values for eutrophication on the basis of region-specific estimates of current nitrogen concentration in run-off and concentrations that would stay below ecological and toxicological thresholds of inorganic nitrogen pollution. The original boundary value for nitrogen was calculated by multiplying the global risk value by an estimate of current anthropogenic nitrogen fixation (fertilizer use plus fixation by crops)[19]. Here we apply the risk values to nitrogen application from fertilizers—in line with the focus in the planetary-boundary literature on anthropogenic disruptions of ecosystems[11,12]—and we use the nitrogen surplus (the sum of fertilizer use, fixation by crops, manure application, human excreta and atmospheric deposition, minus nitrogen offtake by crops) as a control variable in a sensitivity analysis (Extended Data Fig. 3). The resulting estimate of 52–69 TgN per year (67–90 TgN when using nitrogen surplus as a control) might be considered conservative, because the previous study[19] maintained regions that currently apply less than the critical load of nitrogen at that value, which in some cases can be much lower than needed from an environmental and food-security perspective[80]. For that reason, we adopted an upper boundary value in line with a scenario[32] that balanced nitrogen application between overapplying and underapplying regions and closed yield gaps to 75%, which yielded a final boundary value of 69 TgN (range 52–113 TgN) of nitrogen application from fertilizers (90 TgN (range 67–146 TgN) of nitrogen surplus).

Unlike nitrogen, phosphorus can build up in the soil and is washed out as run-off during erosion[7]. Existing estimates of boundary values for phosphorus[18] have several shortcomings in that they are based on constant erosion rates and do not take into account critical sources of phosphorus, such as human waste/excreta. In the previous study[19] a global phosphorus-flow model was developed that focused on added phosphorus assuming steady-state surface pools, critical phosphorus concentrations of 50–100 mg per litre to prevent eutrophication, and flexible recycling rates (Extended Data Fig. 2 and Supplementary Information). Under no-waste recycling, the long-term phosphorus boundary amounted to 6–12 TgP per year, increasing to 8–16 TgP per year at a recycling rate of 50%. In line with our focus on scenarios of change, we adopted the latter values. As with nitrogen, there are great regional imbalances of phosphorus application[81], so we again infer an upper tolerable value from a scenario[32] that rebalanced phosphorus application between overapplying and underapplying regions and closed yield gaps to 75%. The resulting internally derived phosphorus boundary is 16 TgP (range 8–17 TgP) of phosphorus application.

Reporting summary. Further information on research design is available in the Nature Research Reporting Summary linked to this paper.

Data availability

The data that support the findings of this study are available from the Oxford University Research Archive (ORA; https://ora.ox.ac.uk) at https://ora.ox.ac.uk/objects/uuid:d9676f6b-abba-48fd-8d94-cc8c0dc546a2.

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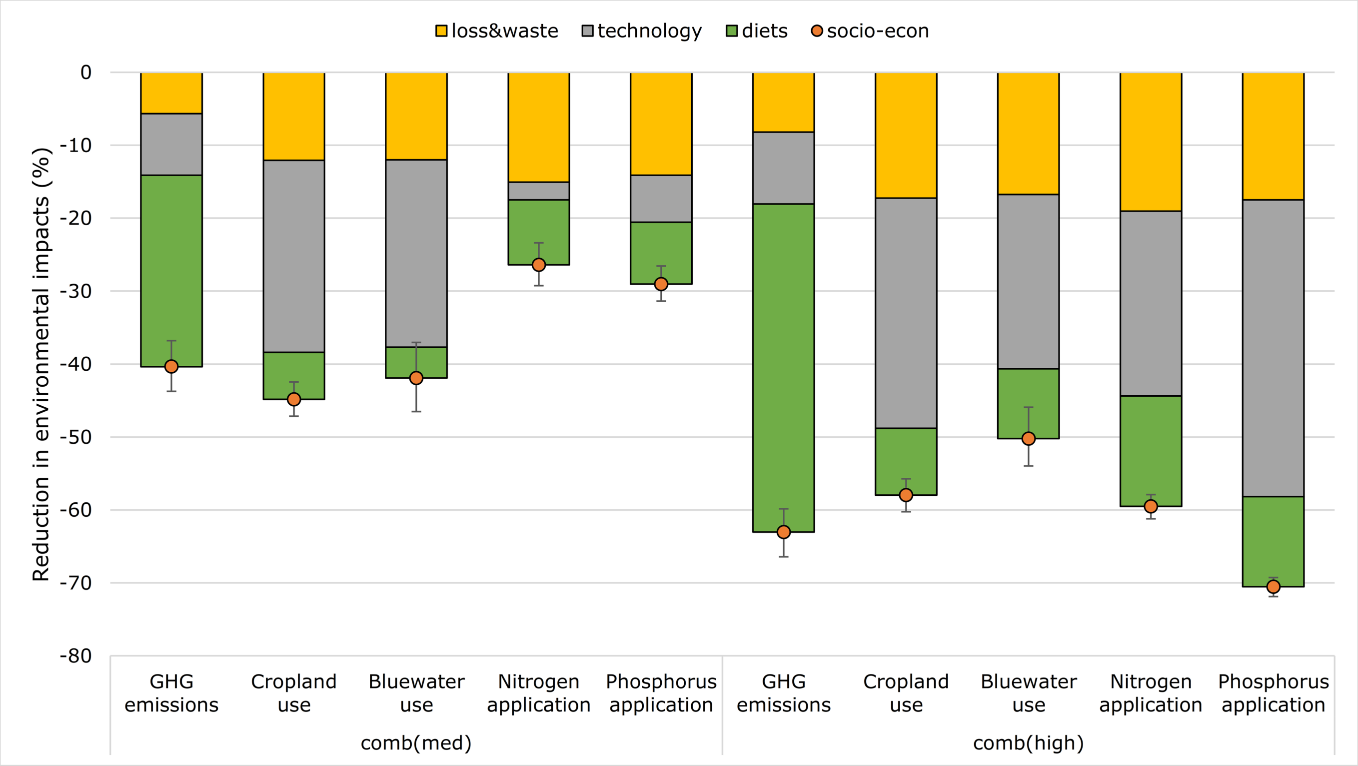
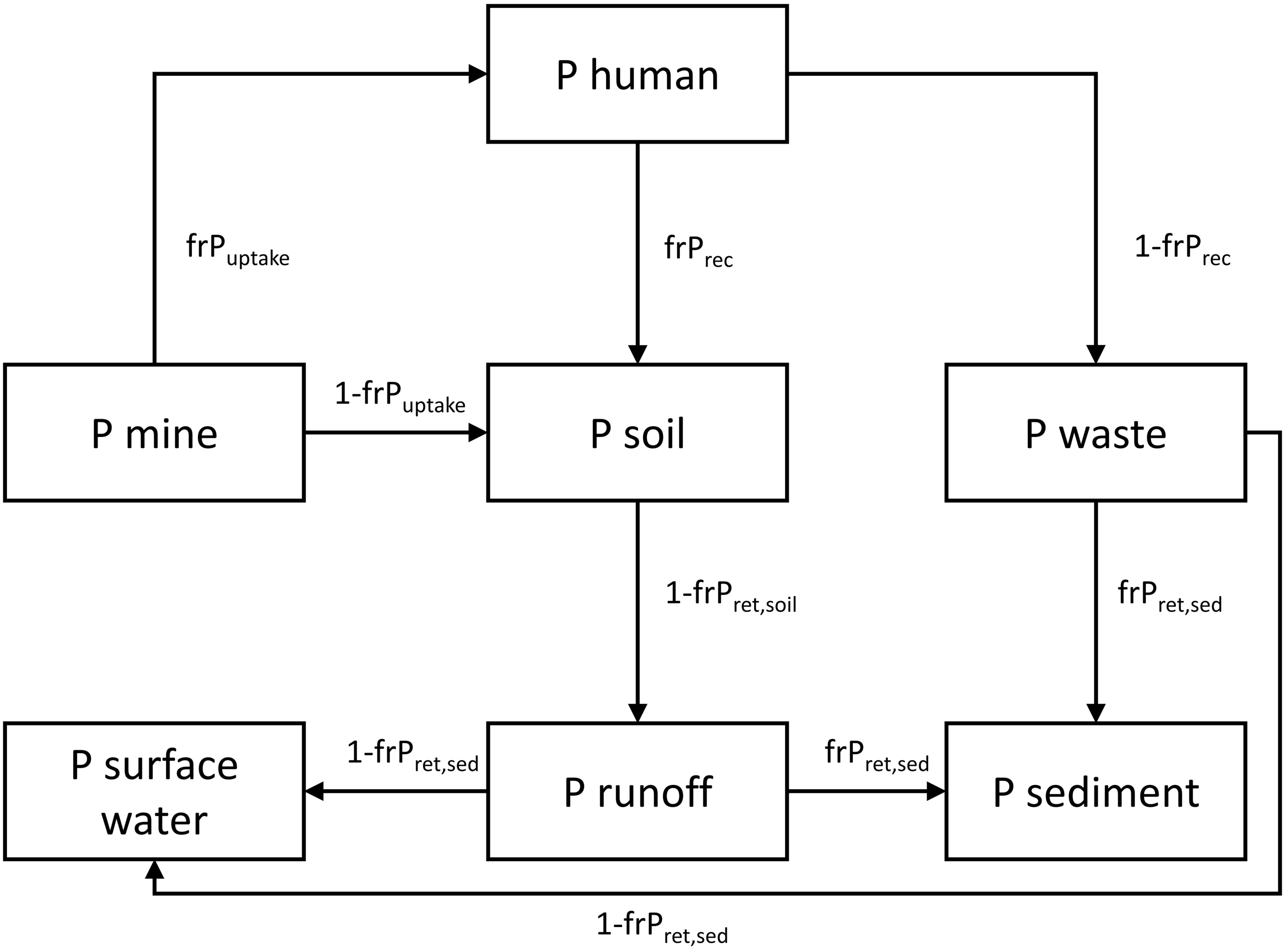
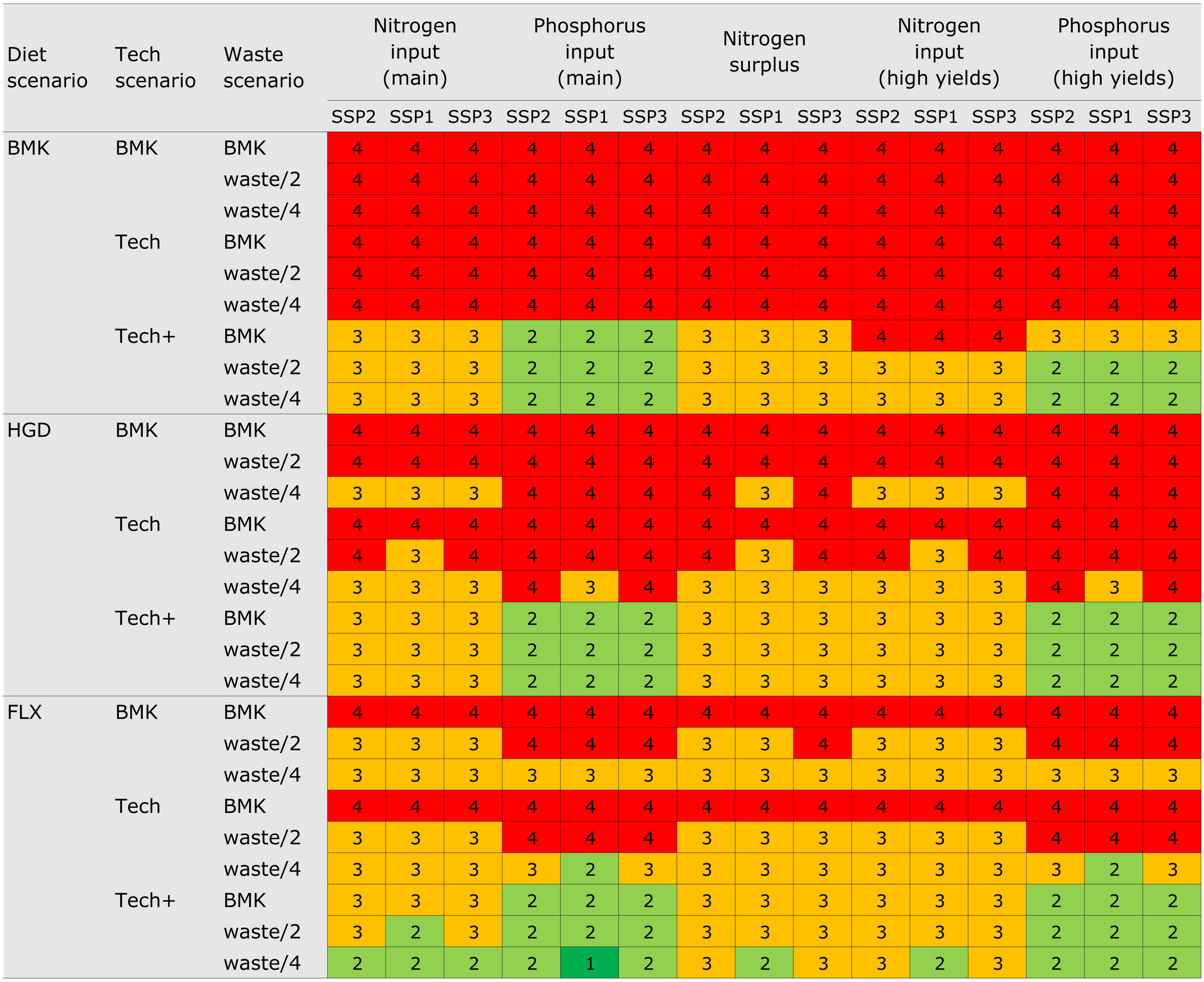


Extended Data Fig. 1 | Reduction in environmental impacts when measures are combined. Shown are combinations of all measures of medium ambition (comb(med)) and of all measures of high ambition (comb(high)). The mitigation measures include changes in food loss and waste (loss&waste), technological change (technology) and dietary change (diets) for a middle-of-the-road development pathway. The differences to development pathways that are more optimistic (higher income and lower population growth) and more pessimistic (lower income and higher population growth) are indicated by the uncertainty range around the markers (socio-econ).



Extended Data Fig. 2 | Overview of major flows of phosphorus at the global scale. The external acceptable phosphorus (P) input is determined by the acceptable long-term accumulation of phosphorus in the soil (P soil) and sediment (P sediment) at a phosphorus concentration in surface waters (P surface water) that equals a critical threshold. The phosphorus boundary is affected by the fraction of phosphorus that is taken up by humans (P human; frP_{uptake} being the P-use efficiency, PUE, of the complete food chain, from mined phosphorus (P mine) to P intake) and the fraction of phosphorus excreted by humans (P waste) that is not recycled to land ($1 - frP_{rec}$), which becomes a point source for water pollution. This phosphorus can only be stored in sediment at a given phosphorus-retention fraction ($frP_{ret,sed}$), while the recycled phosphorus can additionally be stored in soil (at a retention fraction $frP_{ret,soil}$). The critical phosphorus input ($P_{in(crit)}$) can be calculated as the sum of critical phosphorus retention in the soil and sediment, and a critical input to surface water (oceans) that is due to run-off and leaching. The Supplementary Information contains a full derivation of phosphorus flows and quantitative estimates of critical phosphorus inputs.



Diet scenario	Tech scenario	Waste scenario	Nitrogen input (main)			Phosphorus input (main)			Nitrogen surplus			Nitrogen input (high yields)			Phosphorus input (high yields)		
			SSP2	SSP1	SSP3	SSP2	SSP1	SSP3	SSP2	SSP1	SSP3	SSP2	SSP1	SSP3	SSP2	SSP1	SSP3
BMK	BMK	BMK	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
		waste/2	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
		waste/4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	Tech	BMK	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
		waste/2	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
		waste/4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	Tech+	BMK	3	3	3	2	2	2	3	3	3	4	4	4	3	3	3
		waste/2	3	3	3	2	2	2	3	3	3	3	3	3	2	2	2
		waste/4	3	3	3	2	2	2	3	3	3	3	3	3	2	2	2
HGD	BMK	BMK	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
		waste/2	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
		waste/4	3	3	3	4	4	4	4	3	4	3	3	3	4	4	4
	Tech	BMK	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
		waste/2	4	3	4	4	4	4	4	3	4	4	3	4	4	4	4
		waste/4	3	3	3	4	3	4	3	3	3	3	3	3	4	3	4
	Tech+	BMK	3	3	3	2	2	2	3	3	3	3	3	3	2	2	2
		waste/2	3	3	3	2	2	2	3	3	3	3	3	3	2	2	2
		waste/4	3	3	3	2	2	2	3	3	3	3	3	3	2	2	2
FLX	BMK	BMK	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
		waste/2	3	3	3	4	4	4	3	3	4	3	3	3	4	4	4
		waste/4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	Tech	BMK	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
		waste/2	3	3	3	4	4	4	3	3	3	3	3	3	4	4	4
		waste/4	3	3	3	3	2	3	3	3	3	3	3	3	3	2	3
	Tech+	BMK	3	3	3	2	2	2	3	3	3	3	3	3	2	2	2
		waste/2	3	2	3	2	2	2	3	3	3	3	3	3	2	2	2
		waste/4	2	2	2	2	1	2	3	2	3	3	2	3	2	2	2

Extended Data Fig. 3 | Planetary option space related to different control variables of nitrogen and yield-related feedback effects. The control variables include nitrogen inputs related to synthetic fertilizers as used in the main analysis, and the more comprehensive measure of nitrogen surplus that accounts for all inputs and offtakes of nitrogen. The types of feedback effects include changes in nitrogen and phosphorus application associated with closing yield gaps by 75%, as modelled in the tech scenario for cropland use (main), and changes associated with closing yield gaps by 90%, as modelled in the tech+ scenario for cropland use (high yields). Colours and numbers indicate combinations that are below the lower bound of the planetary-boundary range (dark green, 1), below the mean value but above the minimum value (light green, 2), above the mean value but below the maximum (orange, 3), and above the maximum value (red, 4).

Extended Data Table 1 | Scenarios of reductions in food loss and waste, technological change and dietary change

Scenario	Assumptions
Waste/2	Food losses and waste are reduced by half, in line with pledges made as part of the Sustainable Development Goals [29].
Waste/4	Food losses and waste are reduced by three quarters, a value likely close to the maximum value that can be theoretically avoided [30].
Tech	Closing of yield gaps between attained and attainable yields to about 75% [32,33]; Rebalancing nitrogen and phosphorus fertilizer application between over and under-applying regions [32]; improving water management, including increasing basin efficiency, storage capacity, and better utilization of rainwater [33]; and implementation of agricultural mitigation options that are economic at the projected social cost of carbon in 2050, including changes in irrigation, cropping and fertilization 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 [31].
Tech+	Additional measures on top of TECH scenario, including additional increases in agricultural yields that close yield gaps to 90% [32]; a 30% increase in nitrogen use efficiency in line with suggested targets [34], and 50% recycling rates of phosphorus [7]; phase-out of first-generation biofuels [33]; and implementation of all available bottom-up options for mitigating food-related GHG emissions [31].
Guidelines (HGD)	Dietary shifts towards global dietary guidelines, including maximum intakes for red meat (three 100g servings per week) and sugar (5% of energy intake), minimum intakes of fruits and vegetables (five servings a day), and energy intakes in line with recommendations on healthy body weight and physical activity (2100-2200 kcal per day on average) [35,36,70,71].
Flexitarian (FLX)	Dietary shifts towards more plant-based, flexitarian dietary patterns based on recent evidence on healthy eating [37,45,73] that, in addition to the HGD requirements, include more stringent limits for red meat (one serving a week), limits for white meat (half a portion a day) and dairy (one portion a day), and greater minimum amounts of legumes, nuts, and vegetables.

HGD, guidelines; FLX, flexitarian. Data were obtained from previous studies[7,29–37,45,70,71,73].

Extended Data Table 2 | Global food production in 2010 and 2050 differentiated by food group and step along the food chain

Food item	2010								2050							
	prod	trade	intr	feed	othr	loss	waste	cons	prod	trade	intr	feed	othr	loss	waste	cons
wheat	639	114	0	109	47	34	153	295	892	256	0	138	75	51	206	423
rice	430	28	0	24	16	40	33	317	538	59	0	48	19	49	33	390
maize	797	102	0	464	96	123	32	82	1,361	304	0	878	146	156	49	133
other grains	315	45	0	172	38	30	21	55	514	146	0	268	49	55	37	106
roots	767	50	0	164	56	111	109	327	1,145	130	0	167	100	232	153	494
legumes	62	10	0	14	3	2	1	42	113	28	0	22	5	4	1	80
soybeans	225	62	189	10	8	5	0	12	357	98	282	17	22	15	1	21
nuts & seeds	37	14	8	4	4	5	0	16	54	21	9	5	8	11	1	21
vegetables	996	67	0	0	0	124	296	575	1,826	351	0	0	0	206	522	1,098
oilcrops	149	12	145	1	1	2	0	0	227	14	218	1	3	5	0	0
palmcrop	224	0	224	0	0	0	0	0	614	0	614	0	0	0	0	0
oilmeals	83	14	0	83	0	0	0	0	132	31	0	132	0	0	0	0
soybmeal	155	48	0	155	0	0	0	0	232	85	0	232	0	0	0	0
sugarcrops	1,758	0	1,758	0	0	0	0	0	3,396	0	3,396	0	0	0	0	0
fruits (temperate)	206	25	0	0	0	63	50	92	325	57	0	0	0	97	78	150
fruits (tropical)	260	37	0	0	0	26	77	156	462	94	0	0	0	54	130	277
fruits (starchy)	127	21	0	0	0	27	30	70	318	57	0	0	0	82	69	167
sugar	160	44	0	0	5	12	14	129	304	107	0	0	20	24	21	239
palm oil	45	34	0	0	1	28	0	16	124	94	0	0	2	77	1	43
vegetable oil	83	19	0	0	4	24	2	54	122	36	0	1	9	34	2	75
beef	69	9	0	0	0	1	6	63	121	20	0	0	0	1	9	111
lamb	15	2	0	0	0	0	1	13	33	5	0	0	0	0	2	30
pork	105	9	0	0	0	1	9	95	131	31	0	0	0	1	11	120
poultry	85	8	0	0	0	1	7	77	173	30	0	0	0	2	12	158
eggs	66	2	0	0	5	3	4	54	96	10	0	0	8	5	5	78
milk	627	55	0	0	0	35	35	557	1,000	156	0	0	0	67	48	885
shellfish	33	6	0	0	0	0	18	15	49	11	0	0	0	0	27	22
fish (freshwater)	41	4	0	0	0	0	22	19	81	17	0	0	0	0	43	38
fish (pelagic)	17	4	0	0	0	0	9	8	15	5	0	0	0	0	8	7
fish (demersal)	27	7	0	0	0	0	15	12	29	10	0	0	0	0	16	13

Global food production is shown in megatonnes. Steps include consumption (cons), food waste at the household level (waste), food loss at production (loss), industrial and other demand for agricultural products (othr), feed demand (feed), intermediate demand for processing into oils, oil meals and sugar (intr), traded food products (trade; globally, imports equal exports), and total production (prod = cons + waste + loss + othr + feed + intr).

Extended Data Table 3 | Environmental footprints of food commodities (per weight of product)

Food item	GHG intensity (kgCO2/kg)	Cropland use (m2/kg)	Bluewater use (m3/kg)	Nitrogen use (kgN/t)	Phosphorus use (kgP/t)
wheat	0.23	3.36	0.49	28.73	4.39
rice	1.18	3.51	1.07	36.64	5.20
maize	0.19	1.98	0.15	22.77	3.57
other grains	0.29	6.14	0.17	16.36	2.71
roots	0.07	0.69	0.04	3.63	0.71
legumes	0.23	11.02	0.95	0.00	0.00
soybeans	0.12	3.95	0.14	2.75	5.88
nuts & seeds	0.71	6.39	0.43	14.27	2.11
vegetables	0.06	0.49	0.09	9.55	1.67
fruits (temperate)	0.08	1.18	0.33	12.73	1.91
fruits (tropical)	0.09	0.94	0.32	10.27	1.58
fruits (starchy)	0.11	0.85	0.12	6.26	1.07
sugar crops	0.02	0.15	0.11	2.03	0.35
oil crops	0.46	5.45	0.31	31.33	5.61
palm crop	0.38	0.63	0.00	4.57	0.73
sugar	0.19	1.67	1.22	22.34	3.84
palm oil	1.85	3.10	0.00	22.33	3.57
vegetable oil	0.67	10.31	0.47	42.73	11.47
beef	32.49	4.21	0.22	27.29	5.36
lamb	33.02	6.24	0.49	27.51	4.94
pork	2.92	6.08	0.35	51.52	8.87
poultry	1.41	6.59	0.40	50.20	9.02
eggs	1.58	6.86	0.44	51.22	8.81
milk	1.22	1.34	0.08	6.32	1.58
shellfish	0.07	0.36	0.03	3.35	0.81
fish (freshwater)	0.30	1.51	0.10	16.78	3.62
fish (demersal)	0.02	0.12	0.01	1.20	0.29
fish (pelagic)	0.00	0.00	0.00	0.00	0.00

Footprints for animal products represent feed-related impacts, except for GHG emissions of livestock, which also have a direct component. Cropland use does not include grassland use and the use of grass inputs for ruminants. Footprints for fish and seafood represent feed-related impacts of aquaculture production weighted by total production volumes. Displayed are global averages; the regional ordering between food items can differ by region.

Extended Data Table 4 | Reductions in environmental footprints (as percentages) resulting from technological changes by food group

Food item	GHG emissions		Cropland use		Bluewater use		Nitrogen application		Phosphorus application	
	tech	tech+	tech	tech+	tech	tech+	tech	tech+	tech	tech+
wheat	-9.9	-13.8	-31.5	-37.4	-38.6	-38.6	-4.6	-33.2	-15.8	-57.9
rice	-22.4	-27.6	-25.1	-26.7	-17.2	-17.6	0.7	-29.5	-8.7	-54.3
maize	-9.7	-12.5	-32.6	-36.8	-24.6	-24.7	-10.7	-37.5	-17.8	-58.9
other grains	-10.5	-15.6	-39.6	-37.3	-27.1	-27.2	5.9	-25.9	-13.6	-56.8
roots	0.0	0.0	-32.4	-43.7	-27.5	-28.0	0.0	-30.0	0.0	-50.0
legumes	-8.8	-12.6	-38.1	-49.9	-32.3	-32.4	0.0	0.0	0.0	0.0
soybeans	-9.3	-12.4	-19.6	-2.9	10.1	9.8	0.0	-30.0	0.0	-50.0
nuts & seeds	0.0	0.0	-23.9	-35.2	-12.8	-12.8	0.0	-30.0	0.0	-50.0
vegetables	0.0	0.0	-35.4	-47.1	-39.3	-39.6	0.0	-30.0	0.0	-50.0
fruits (temperate)	0.0	0.0	-18.2	-45.5	-25.5	-25.8	0.0	-30.0	0.0	-50.0
fruits (tropical)	0.0	0.0	-35.9	-50.0	-46.1	-46.1	0.0	-30.0	0.0	-50.0
fruits (starchy)	0.0	0.0	-40.4	-57.7	-25.1	-25.1	0.0	-30.0	0.0	-50.0
sugar	0.0	0.0	-20.5	-21.2	-26.1	-26.1	0.0	-30.0	0.0	-50.0
palm oil	0.0	0.0	-22.4	-23.8	-59.1	-59.1	0.0	-30.0	0.0	-50.0
vegetable oil	-1.2	-1.5	-18.5	-43.1	-4.7	-4.9	0.0	-30.0	0.0	-50.0
beef	-9.1	-10.7	-31.4	-34.4	-25.6	-25.6	-2.2	-31.5	-13.2	-56.6
lamb	-8.6	-10.2	-35.7	-42.3	-23.9	-24.0	-1.6	-31.1	-13.2	-56.6
pork	-11.8	-15.5	-29.6	-32.6	-24.7	-25.2	-9.3	-36.5	-15.3	-57.6
poultry	-11.0	-13.6	-31.6	-34.3	-26.0	-26.1	-8.8	-36.1	-16.6	-58.3
eggs	-12.5	-15.4	-30.6	-35.3	-26.5	-26.9	-12.5	-38.8	-17.7	-58.8
milk	-9.8	-12.0	-26.3	-34.5	-16.4	-16.5	-0.2	-30.1	-5.6	-52.8
shellfish	-10.1	-12.9	-22.7	-35.3	-24.0	-24.2	-2.0	-31.4	-4.9	-52.5
fish (freshwater)	-4.7	-6.2	-22.5	-37.2	-18.9	-19.0	-3.9	-32.7	-5.6	-52.8
fish (demersal)	-5.9	-7.8	-22.5	-35.5	-22.7	-22.9	-3.8	-32.7	-5.4	-52.7
fish (pelagic)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Technological changes include changes of medium ambition (tech) and changes of high ambition (tech+). Zero entries indicate where no data were available to infer potential improvements, and for pelagic fish reflect a production method (marine fishing) that does not require feed inputs.

Extended Data Table 5 | Food-based dietary recommendations for healthy, more plant-based (flexitarian) diets

Food item	minimum level		maximum level	
	g/d	serving	g/d	serving
wheat			A total of up to 860 kcal/d for energy balance for all staple crops	3-4 (1/3 of energy)
rice				
maize				
other grains				
roots				
legumes	50	1/2		
soybeans	25	1/4		
nuts & seeds	50	2		
vegetables	300	3-4		
fruits	200	2-3		
sugar			31	5% of energy
palm oil			6.8	1
vegetable oil			80	1/3 of energy
beef			A total of 14 g/d for all red meat	1/7
lamb				
pork				
poultry			29	1/2
eggs			13	1/5
milk			250	1
shellfish	A total of 28 g/d for all fish and seafood	1/2		
fish (freshwater)				
fish (demersal)				
fish (pelagic)				

The recommendations include recommended minimum and maximum intakes expressed as weight or calories, and servings. Fish and seafood can be replaced by plant-based foods (legumes, soybeans, nuts and seeds, fruits and vegetables) in vegetarian diets. Units are g or kcal per day.

Extended Data Table 6 | Decomposition of impacts of dietary scenarios

Indicator	Diet scenario	Change in environmental impacts by food group							
		total	staples	legumes	nuts& seeds	fruits& veg	veg oils	sugar	animal products
GHG emissions (MtCO2-eq)	HGD(E=BMK)	-2,513	113	-4	-1	43	-3	-30	-2,631
	HGD	-2,850	-224	-4	-1	43	-3	-30	-2,631
	FLX	-5,063	-497	35	28	59	-7	-30	-4,651
Cropland use (1000 km2)	HGD(E=BMK)	919	1,596	0	0	450	0	-257	-870
	HGD	-1,540	-864	0	0	450	0	-257	-870
	FLX	-2,307	-2,340	1,092	407	486	716	-257	-2,415
Bluewater use (km3)	HGD(E=BMK)	201	227	0	0	244	0	-215	-56
	HGD	-136	-113	0	0	245	0	-215	-56
	FLX	-332	-394	110	39	220	48	-214	-143
Nitrogen application (GgN)	HGD(E=BMK)	3,587	10,782	0	0	2,827	1	-3,322	-6,703
	HGD	-14,784	-7,537	0	0	2,811	-4	-3,324	-6,719
	FLX	-29,723	-17,082	241	672	5,081	1,660	-3,327	-16,935
Phosphorus application (GgP)	HGD(E=BMK)	324	1,719	0	0	435	0	-570	-1,261
	HGD	-2,542	-1,136	0	0	432	-1	-571	-1,264
	FLX	-4,464	-2,670	416	118	856	607	-571	-3,212

Impacts (shown as absolute changes with respect to the baseline projection in 2050) are decomposed into changes by food group and energy intake. In the (E = BMK) scenario, only dietary composition is changed, whereas in the main scenarios, dietary composition and energy intake are changed in line with dietary guidelines and current evidence on healthy eating.

Extended Data Table 7 | Derivation of planetary-boundary values of the food system

Planetary boundary	Motivation	Method	Boundary
Climate change	Further increasing GHG emissions increase climate-related risks to ecosystems and cultures, e.g. from sea-level rise and increased occurrence of extreme weather events, such as heat waves, extreme precipitation, and coastal flooding [82].	Food-related GHG emissions in line with limiting global warming to below 2 degrees Celsius [63] with uncertainty derived from a model comparison of integrated assessment models [58].	A budget of 4.7 (4.3-5.3) $GtCO_2$-eq of food-related GHG emissions, including methane and nitrous oxide, but excluding carbon dioxide in line with IPCC methodology.
Land-system change	Further increasing the amount of agricultural land through deforestation could impact the functioning of ecosystems [3], release large amounts of carbon dioxide [1], and diminish habitat for wild species and thereby pose major threats to biodiversity [4].	Analysis of conservation levels for each forest biome in line with preserving ecosystem integrity, scaled up to a global value [12] and related to cropland use [33,39].	Not increasing pressures on forests by keeping global cropland use at 12.6 (10.6-14.6) Mkm^2. Converting productive grazing land into cropland can relax the boundary value.
Freshwater use	Further depletion and overexploitation of groundwater resources impairs natural streamflow, wetlands and related ecosystems, and can lead to land subsidence and salt-water intrusion in deltaic areas [6] and, eventually, to cascading impacts on the global hydrological cycle [77].	Basin-level assessments of the environmental flow requirements of river systems [12,20] scaled to agricultural bluewater use [5,33].	Maintaining environmental flow requirements by limiting agricultural bluewater use to 1,980 (780-3,190) km^3 or below.
Bio-geochemical flows of nitrogen and phosphorus	Agricultural runoff from overapplication of fertilizers leads to eutrophication, an increase in chemical nutrients in the water [7,9], which in turn can lead to excessive blooms of algae that deplete underwater oxygen levels resulting in so-called dead zones in coastal oceans [8].	Analysis of eutrophication risk based on nitrogen and phosphorus pollution estimates of agricultural runoff and ecological thresholds [19], with an upper value in line with re-balancing of application between over and under-applying regions [32].	Limiting nitrogen and phosphorus application from fertilizers to 69 (52-113) TgN and 16 (8-17) TgP respectively.

IPCC, Intergovernmental Panel on Climate Change. Data were obtained from previous studies[1,3–9,12,19,20,33,39,58,63,77,82].

nature research

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Reporting Summary

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Statistical parameters

When statistical analyses are reported, confirm that the following items are present in the relevant location (e.g. figure legend, table legend, main text, or Methods section).

n/a	Confirmed	
☒	☐	The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement
☒	☐	An indication of whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☒	☐	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☒	☐	A description of all covariates tested
☒	☐	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☒	☐	A full description of the statistics including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☒	☐	For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐	Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated
☐	☒	Clearly defined error bars *State explicitly what error bars represent (e.g. SD, SE, CI)*

Our web collection on statistics for biologists may be useful.

Software and code

Policy information about availability of computer code

Data collection	Data processing was carried out using GAMS (General Algebraic Modeling System), version 24.5.5.
Data analysis	Data analysis was carried out using GAMS (General Algebraic Modeling System), version 24.5.5.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors/reviewers upon request. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A list of figures that have associated raw data
- A description of any restrictions on data availability

The results generated for the study are available in from the Oxford University Research Archive (ORA; https://ora.ox.ac.uk) at https://ora.ox.ac.uk/objects/uuid:d9676f6b-abba-48fd-8d94-cc8c0dc546a2. Additional data are available upon request.

Field-specific reporting

Please select the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☒ Behavioural & social sciences

For a reference copy of the document with all sections, see nature.com/authors/policies/ReportingSummary-flat.pdf

Life sciences

Study design

All studies must disclose on these points even when the disclosure is negative.

Sample size	*Describe how sample size was determined, detailing any statistical methods used to predetermine sample size OR if no sample-size calculation was performed, describe how sample sizes were chosen and provide a rationale for why these sample sizes are sufficient.*
Data exclusions	*Describe any data exclusions. If no data were excluded from the analyses, state so OR if data were excluded, describe the exclusions and the rationale behind them, indicating whether exclusion criteria were pre-established.*
Replication	*Describe the measures taken to verify the reproducibility of the experimental findings. If all attempts at replication were successful, confirm this OR if there are any findings that were not replicated or cannot be reproduced, note this and describe why.*
Randomization	*Describe how samples/organisms/participants were allocated into experimental groups. If allocation was not random, describe how covariates were controlled OR if this is not relevant to your study, explain why.*
Blinding	*Describe whether the investigators were blinded to group allocation during data collection and/or analysis. If blinding was not possible, describe why OR explain why blinding was not relevant to your study.*

Materials & experimental systems

Policy information about availability of materials

n/a	Involved in the study
☐	☐ Unique materials
☐	☐ Antibodies
☐	☐ Eukaryotic cell lines
☐	☐ Research animals
☐	☐ Human research participants

Unique materials

Obtaining unique materials	*Describe any restrictions on the availability of unique materials OR confirm that all unique materials used are readily available from the authors or from standard commercial sources (and specify these sources).*

Antibodies

Antibodies used	*Describe all antibodies used in the study; as applicable, provide supplier name, catalog number, clone name, and lot number.*
Validation	*Describe the validation of each primary antibody for the species and application, noting any validation statements on the manufacturer's website, relevant citations, antibody profiles in online databases, or data provided in the manuscript.*

Eukaryotic cell lines

Policy information about cell lines

Cell line source(s)	*State the source of each cell line used.*
Authentication	*Describe the authentication procedures for each cell line used OR declare that none of the cell lines used were authenticated.*
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Research animals

Policy information about studies involving animals; ARRIVE guidelines recommended for reporting animal research

Animals/animal-derived materials	*For laboratory animals, report species, strain, sex and age OR for animals observed in or captured from the field, report species, sex and age where possible.*

Human research participants

Policy information about studies involving human research participants

Population characteristics	*Describe the covariate-relevant population characteristics of the human research participants (e.g. age, gender, genotypic information, past and current diagnosis and treatment categories).*

Method-specific reporting

n/a	Involved in the study
☐	☐ ChIP-seq
☐	☐ Flow cytometry
☐	☐ Magnetic resonance imaging

ChIP-seq

Data deposition

☐ Confirm that both raw and final processed data have been deposited in a public database such as GEO.

☐ Confirm that you have deposited or provided access to graph files (e.g. BED files) for the called peaks.

Data access links *May remain private before publication.*	*For "Initial submission" or "Revised version" documents, provide reviewer access links. For your "Final submission" document, provide a link to the deposited data.*
Files in database submission	*Provide a list of all files available in the database submission.*
Genome browser session (e.g. UCSC)	*Provide a link to an anonymized genome browser session for "Initial submission" and "Revised version" documents only, to enable peer review. Write "no longer applicable" for "Final submission" documents.*

Methodology

Replicates	*Describe the experimental replicates, specifying number, type and replicate agreement.*
Sequencing depth	*Describe the sequencing depth for each experiment, providing the total number of reads, uniquely mapped reads, length of reads and whether they were paired- or single-end.*
Antibodies	*Describe the antibodies used for the ChIP-seq experiments; as applicable, provide supplier name, catalog number, clone name, and lot number.*
Peak calling parameters	*Specify the command line program and parameters used for read mapping and peak calling, including the ChIP, control and index files used.*
Data quality	*Describe the methods used to ensure data quality in full detail, including how many peaks are at FDR 5% and above 5-fold enrichment.*
Software	*Describe the software used to collect and analyze the ChIP-seq data. For custom code that has been deposited into a community repository, provide accession details.*

Flow Cytometry

Plots

Confirm that:

☐ The axis labels state the marker and fluorochrome used (e.g. CD4-FITC).

☐ The axis scales are clearly visible. Include numbers along axes only for bottom left plot of group (a 'group' is an analysis of identical markers).

☐ All plots are contour plots with outliers or pseudocolor plots.

☐ A numerical value for number of cells or percentage (with statistics) is provided.

Methodology

Sample preparation	*Describe the sample preparation, detailing the biological source of the cells and any tissue processing steps used.*
Instrument	*Identify the instrument used for data collection, specifying make and model number.*
Software	*Describe the software used to collect and analyze the flow cytometry data. For custom code that has been deposited into a community repository, provide accession details.*
Cell population abundance	*Describe the abundance of the relevant cell populations within post-sort fractions, providing details on the purity of the samples and how it was determined.*
Gating strategy	*Describe the gating strategy used for all relevant experiments, specifying the preliminary FSC/SSC gates of the starting cell population, indicating where boundaries between "positive" and "negative" staining cell populations are defined.*

☐ Tick this box to confirm that a figure exemplifying the gating strategy is provided in the Supplementary Information.

Magnetic resonance imaging

Experimental design

Design type	*Indicate task or resting state; event-related or block design.*
Design specifications	*Specify the number of blocks, trials or experimental units per session and/or subject, and specify the length of each trial or block (if trials are blocked) and interval between trials.*
Behavioral performance measures	*State number and/or type of variables recorded (e.g. correct button press, response time) and what statistics were used to establish that the subjects were performing the task as expected (e.g. mean, range, and/or standard deviation across subjects).*

Acquisition

Imaging type(s)	*Specify: functional, structural, diffusion, perfusion.*
Field strength	*Specify in Tesla*
Sequence & imaging parameters	*Specify the pulse sequence type (gradient echo, spin echo, etc.), imaging type (EPI, spiral, etc.), field of view, matrix size, slice thickness, orientation and TE/TR/flip angle.*
Area of acquisition	*State whether a whole brain scan was used OR define the area of acquisition, describing how the region was determined.*

Diffusion MRI ☐ Used ☐ Not used

Preprocessing

Preprocessing software	*Provide detail on software version and revision number and on specific parameters (model/functions, brain extraction, segmentation, smoothing kernel size, etc.).*
Normalization	*If data were normalized/standardized, describe the approach(es): specify linear or non-linear and define image types used for transformation OR indicate that data were not normalized and explain rationale for lack of normalization.*
Normalization template	*Describe the template used for normalization/transformation, specifying subject space or group standardized space (e.g. original Talairach, MNI305, ICBM152) OR indicate that the data were not normalized.*
Noise and artifact removal	*Describe your procedure(s) for artifact and structured noise removal, specifying motion parameters, tissue signals and physiological signals (heart rate, respiration).*
Volume censoring	*Define your software and/or method and criteria for volume censoring, and state the extent of such censoring.*

Statistical modeling & inference

Model type and settings	*Specify type (mass univariate, multivariate, RSA, predictive, etc.) and describe essential details of the model at the first and second levels (e.g. fixed, random or mixed effects; drift or auto-correlation).*
Effect(s) tested	*Define precise effect in terms of the task or stimulus conditions instead of psychological concepts and indicate whether ANOVA or factorial designs were used.*

Specify type of analysis: ☐ Whole brain ☐ ROI-based ☐ Both

Statistic type for inference (See Eklund et al. 2016)	*Specify voxel-wise or cluster-wise and report all relevant parameters for cluster-wise methods.*
Correction	*Describe the type of correction and how it is obtained for multiple comparisons (e.g. FWE, FDR, permutation or Monte Carlo).*

Models & analysis

n/a	Involved in the study
☐	☐ Functional and/or effective connectivity
☐	☐ Graph analysis
☐	☐ Multivariate modeling or predictive analysis

Functional and/or effective connectivity	*Report the measures of dependence used and the model details (e.g. Pearson correlation, partial correlation, mutual information).*
Graph analysis	*Report the dependent variable and connectivity measure, specifying weighted graph or binarized graph, subject- or group-level, and the global and/or node summaries used (e.g. clustering coefficient, efficiency, etc.).*
Multivariate modeling and predictive analysis	*Specify independent variables, features extraction and dimension reduction, model, training and evaluation metrics.*

Behavioural & social sciences

Study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Quantitative analysis
Research sample	N/A
Sampling strategy	N/A
Data collection	This study used existing datasets.
Timing	N/A
Data exclusions	N/A
Non-participation	N/A
Randomization	N/A