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Options for keeping the food system within environmental limits

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Abstract

The food system is a major driver of climate change, land-use change, depletion of freshwater resources, and pollution of aquatic and terrestrial ecosystems by excessive nitrogen and phosphorus inputs. Here we show that as a result of expected changes in population and income levels, the environmental impacts of the food system could increase by 60-90% between 2010 and 2050 in absence of technological changes and dedicated mitigation measures, and reach levels that are beyond planetary boundaries that define a safe operating space for humanity. We analyse several options for reducing the environmental impacts 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 simultaneously stay within all planetary boundaries, and combining each measure synergistically will be needed to sufficiently mitigate the projected increase in environmental pressures.

Introduction

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 runoff 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 for climate change, biosphere integrity, and biogeochemical flows related to nitrogen and phosphorous cycles. If socio-economic 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 destabilised and losing the regulation functions on which populations depend [11,12].

Here we analyse the option space 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 [22–24]. The planetary-boundary framework is not without criticism, in particular due to 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 that, we consider the planetary-boundary framework useful for framing, in broad terms, the planetary options 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 (Methods), and by reporting the environmental impacts in absolute terms (e.g. emissions in tonnes of carbon dioxide equivalents), which allows for comparisons to other measures of environmental sustainability.

We advance the current 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 (Methods). The model's regional detail 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 current 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 characterise 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 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 on food loss and waste align with and exceed commitments made as part of the Sustainable Development Goals [28–30]. The scenarios of technological change account for future improvements in agricultural yields, fertilizer application, increases in feed efficiency, and changes in management practices [31–34]. And the scenarios of dietary change include changes towards dietary guidelines and dietary patterns in line with the current evidence on healthy eating [35–37].

In our baseline trajectory, we account for different socio-economic pathways of population and income growth [33], and project forward future demand for environmental resources in 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, it is uncertain what level of ambition those will have 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 (e.g. 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 (e.g. reducing food loss and waste by 75%).

Environmental impacts of the food system

Our analysis indicates that current and projected levels of agricultural production significantly impact the Earth's environment in absence of targeted mitigation measures. We estimate that in 2010, the food system emitted about 5.2 $GtCO_2$-eq of GHG emissions in the form of methane and nitrous oxide, occupied 12.6 million km^2 of cropland, used 1,810 km^3 of freshwater resources from surface and groundwater (bluewater), and applied 104 TgN and 18 TgP in the form of nitrogen and phosphorus fertilizers (Supplementary Data File). Our estimates are comparable to previous estimates of food-related GHG emissions of 4.6-5.8 GtCO2 [1,38], global cropland use of 12.2-17.1 million km^2 in 2000 [39], bluewater use in 2000 of

1,700-2,270 km^3 [5,20], and nitrogen and phosphorus application of 104 TgN [40] and 15.8-18.8 TgP [40,41].

Food production and consumption are projected to change between 2010 and 2050 (Extended Data Table 2) as a result of expected socio-economic developments (Supplementary Table 1). Those include the global population growing by about a third (with a range of 23-45%, from 6.9 billion to 8.5-10 billion) and global income tripling (with a range of 2.6-4.2, from $68 trillion to $180-290 trillion) [33]. As a result of those changes, we project 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 (Figure 1). The greatest increase along this baseline pathway are projected for GHG emissions (87% 80-92), followed by the demand for cropland use (67%, 66-68), bluewater use (65%, 64-65), nitrogen application (51%, 50-52), and phosphorus application (54%, 51-55).

Specific food groups vary in their environmental impacts (Figure 1). The production of animal products generates the majority of food-related GHG emissions (72-78% of total agricultural emissions), which is due to their low feed-conversion efficiencies, enteric fermentation in ruminants, and manure-related emissions [42], and the feed-related impacts of animal products also contribute to bluewater use (~10%) and pressures on cropland, and nitrogen and phosphorus application (20-25% each). In 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), 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. Currently 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%, a value likely close to the maximum theoretically avoidable value [30]. We estimate that halving food loss and waste (*waste/2*) would reduce environmental pressures by 6-16% compared to the baseline projection for 2050, and that reducing food loss and waste by 75% (*waste/4*) would reduce environmental pressures by 9-24% (Figure 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 in agricultural yields which reduce the demand for additional cropland [32,33]; rebalancing of fertilizer application between over and under-applying regions [32] which, together with increasing nitrogen use efficiency [34,43] and recycling of phosphorus [7], reduces 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, as well as changes in manure management, feed conversion and feed additives that reduce enteric fermentation in livestock [31]. We estimate that implementing those measures could reduce the environmental pressures of the food system in scenarios of medium ambition (*tech*) by 3-30% compared to the baseline projection for 2050, and by 11-54% in scenarios of high ambition (*tech+*) (Figure 2). In each case, the higher-end estimates are for the staple crop-dominated environmental domains (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 whose large share of livestock-related emissions are, to a large extent, inherent characteristics of the animals and therefore cannot be reduced more substantially with existing mitigation options (Extended Data Table 4) [31,44].

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, 5). We estimate that, compared to 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 (*HGD*), and by 56% and 6-22%, respectively, for the more plant-based diet scenario (*FLX*) (Figure 2). The changes are in line with the dietary composition of the diets and the environmental footprints of each food group (Figure 1, Extended Data Table 1, Supplementary Table 2). Changes in meat consumption dominate the impacts on GHG emissions, whilst for the other domains the environmental pressures associated with greater consumption of fruits, vegetables, nuts, and legumes are more significant but outweighed by the environmental benefits associated with lower consumption of meat, staple crops, sugar, and a generally lower energy intake in line with healthy bodyweights and recommended levels of physical activity [35] (Extended Data Table 6).

To inform how the combined implementation of some or all of the discussed measures could impact 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 (Figure 2). Combining all measures of medium ambition [*comb(med)*] could reduce environmental pressures by around 25-45% compared to the baseline projection for 2050, resulting in total environmental impacts that are within 15% above and below current impacts, whereas combining all measures of high ambition [*comb(high)*] 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, whilst reductions in food loss and waste contribute up to a third to the overall reductions (Extended Data Figure 1).

Planetary option space

What level of reduction in environmental pressures should be aimed for? We can explore this question by 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 Figure 2, Methods). According to our quantification, the planetary boundaries (*PB*) define a space around the current values for most environmental domains, with a mean value slightly below for food-related GHG emissions, at current values for cropland use, slightly above for bluewater use, and significantly below for nitrogen and phosphorus application (Figure 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 to be 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 (Figure 2). An analysis of the planetary option space details the possible combination of measures (Figure 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 socio-economic development pathway that includes lower population and higher income growth than is currently expected. 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 socio-economic development pathway (Figure 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 for bluewater use, and nitrogen and phosphorus application (see Methods). The planetary boundary framework can therefore only provide 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 (Figure 3), and e.g. does not require reductions in food loss and waste or a more optimistic socio-economic development pathway, whereas meeting the lower bound of the planetary-boundary range would 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 impact the option space. However, assessing the impacts of nitrogen pollution based on a measure of nitrogen surplus that accounts for all inputs and offtakes of nitrogen had little influence on the option space (Extended Data Figure 3).

Other uncertainties are related to the setup of our modelling framework. Although we considered some feedbacks between the different measures of change, in particular between changes in yields and the demand for bluewater, nitrogen and phosphorus use, this was limited to the scenarios of medium ambition (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 feedbacks that very high yield-gap closures 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 Figure 3). In line with our focus on mitigation measures, we also abstracted from the impacts that climate change could have on crop yields and freshwater availability [46]. Whilst 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 either realistic, attainable, or have been set as goals. This means we did not include technologies or mitigation measures with currently large uncertainties, 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 clear yet whether they are scalable and what their relationship to existing technologies and environmental targets would be [48]. For example, land-based carbon sequestration, whilst 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, e.g. on health [15], biodiversity [49], and the economy [47], as well as context-specific metrics of sustainability and a greater focus on livelihood, e.g. in terms of food security [50].

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 socio-economic development.

Implementation of these measures will depend on the regulatory and incentive framework in each region. Practical options exist in particular 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, e.g. of water use and quality. Concrete options also exist to improve socio-economic development in developing countries, including investments in education, in particular for women, and improving access to general and reproductive health services [51]. 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 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 [52,53]. 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 [53]. An important first step would be to align national food-based dietary guidelines with the current evidence on healthy eating and the environmental impacts of diets [54,55].

Our analysis suggests that the environmental impacts of the food system could increase dramatically due to expected changes in food consumption and production, and in absence of targeted measures would exceed planetary boundaries above which key ecosystem processes become at risk of being destabilised. Synergistically combining the measures of 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 for defining region-specific pathways for the sustainable development of food systems within the planetary option space. We hope the country-specific data and suite of scenarios produced for this study can provide a good starting point for this endeavour (Supplementary Data File).

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Author contributions

MS designed the study, compiled the models, conducted the analysis, interpreted the results, and wrote the manuscript. KW, DMD, and MC contributed data and model components for the food systems model. BLB, LL, and WV contributed data and model components for the analysis of nitrogen and phosphorus. SJV, MH, and KMC contributed data for the analysis of greenhouse gas emissions. MJ and MT contributed data for the analysis of fish and seafood. WW designed the flexitarian diet and contributed to the discussion on the health aspects of dietary change. FD contributed to the discussion on the planetary boundary related to land use. LJG and RZ contributed to the discussion on water use. PS and MR and contributed to the discussion on the health aspects of dietary change. BL facilitated discussions and contributed to the discussion on the planetary boundaries related to the food system. JF contributed to the discussion and background of the study. JR, HCJG, GDT contributed to the 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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Declaration of interest

We have no competing interests.

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Supplementary Information

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Main table and figure legends

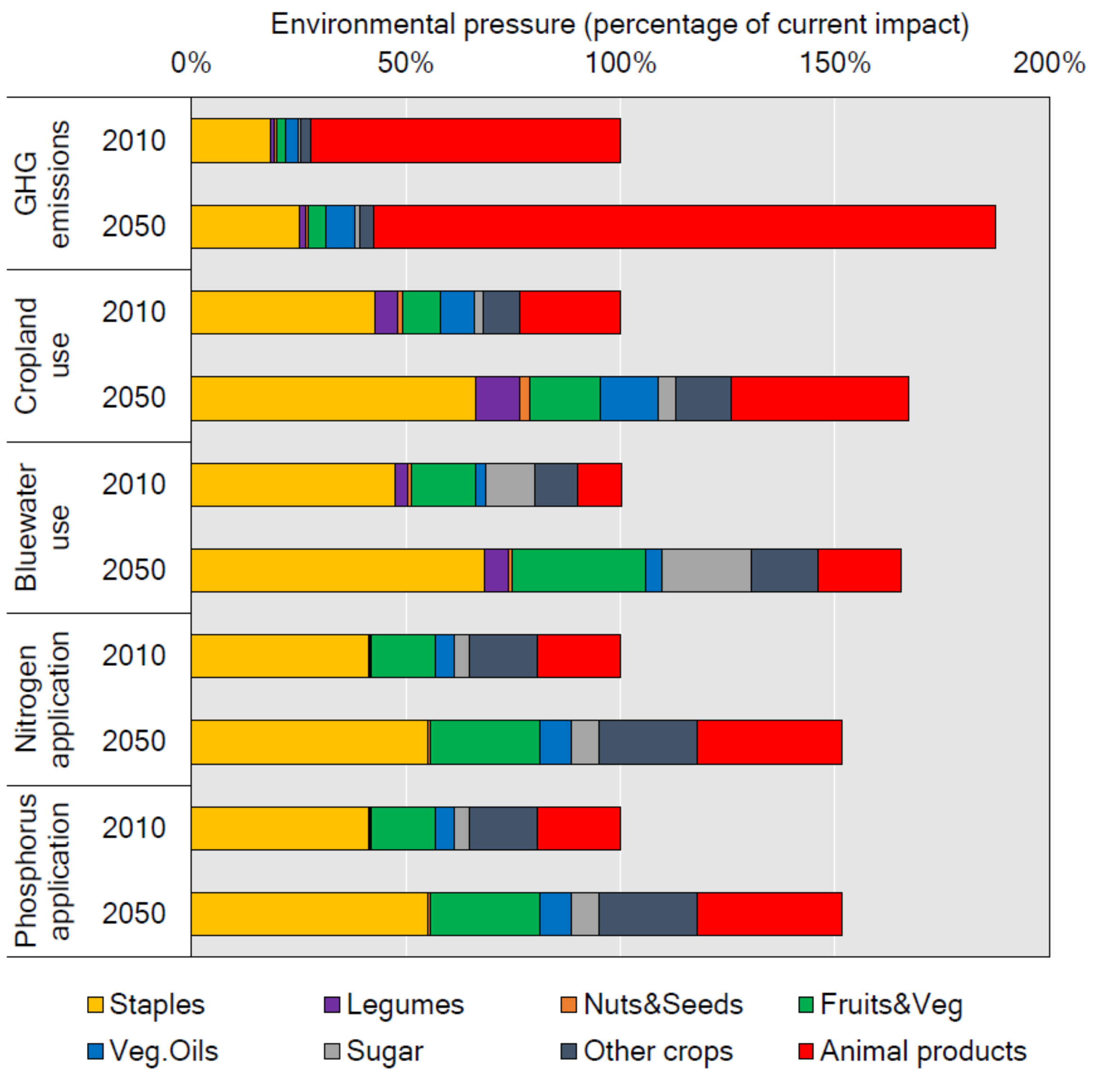

Figure 1. Current and projected environmental pressures in 2010 and 2050 on five environmental domains by food group. Environmental pressures are allocated to the final product, accounting for the use and impacts of primary products in the production of vegetable oils and refined sugar, and for feed requirements in animal products. Impacts are shown as percentage of current impacts for a baseline projection without dedicated mitigation measures for a middle-of-the-road socio-economic development pathway (SSP2). Absolute impacts for all socio-economic pathways are provided in the text and the Supplementary Datafile.

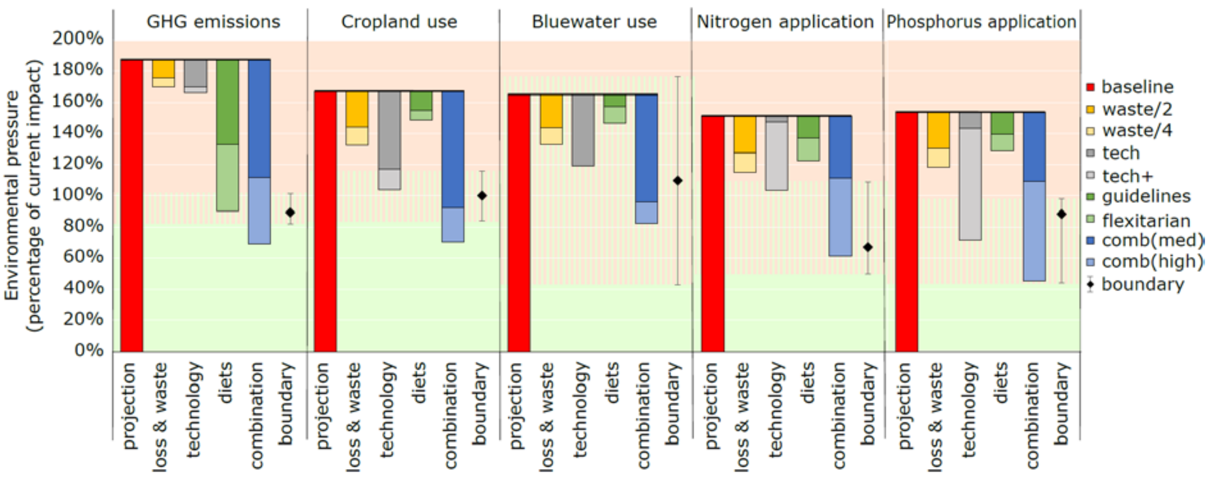

Figure 2. Impacts of reductions in food loss and waste, technological change, and dietary changes on global environmental pressures in 2050. The projections of environmental pressures in 2050 are baseline projections without dedicated mitigation measures for a middle-of-the-road development pathway and expressed as percentage of current 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 (e.g. the diets bar ending at 90% of current impacts of GHG emissions indicates that ambitious dietary changes (flexitarian, *FLX*) can reduce the projected increase of GHG emissions from 187% of current impacts to 90% which represents a reduction of 52% or 97 percentage points, whereas dietary changes of medium ambition (guidelines, *HGD*), which in the figure end at the split line of the diets bar, can reduce GHG emissions from 187% of current 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 technological changes to 2050 (*tech*) and more ambitious technological changes (*tech+*). The diet scenarios include diets aligned with global dietary guidelines (guidelines, *HGD*), and more plant-based, flexitarian diets (flexitarian, *FLX*) that are reflective of the current 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*] including an optimistic socio-economic 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 green/light red hatched: between minimum and maximum values; light red: above maximum values).

Diet scenario	Tech scenario	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
BMK	BMK	BMK	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	BMK	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+	BMK	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
HGD	BMK	BMK	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	BMK	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+	BMK	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
FLX	BMK	BMK	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	BMK	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+	BMK	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

Figure 3. Planetary option space. Combinations of dietary change (*HGD*, *FLX*), technological change (*tech*, *tech+*), changes in food loss and waste (*waste/2*, *waste/4*), and socio-economic development pathways (*SSP2, SSP1, SSP3*). Changes are applied to baseline conditions in 2050 (*BMK*). The diet scenarios include diets aligned with global dietary guidelines (*HGD*), and more plant-based, flexitarian diets (*FLX*) 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 technological changes to 2050 (*tech*) and more ambitious technological changes (*tech+*). The socio-economic 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).

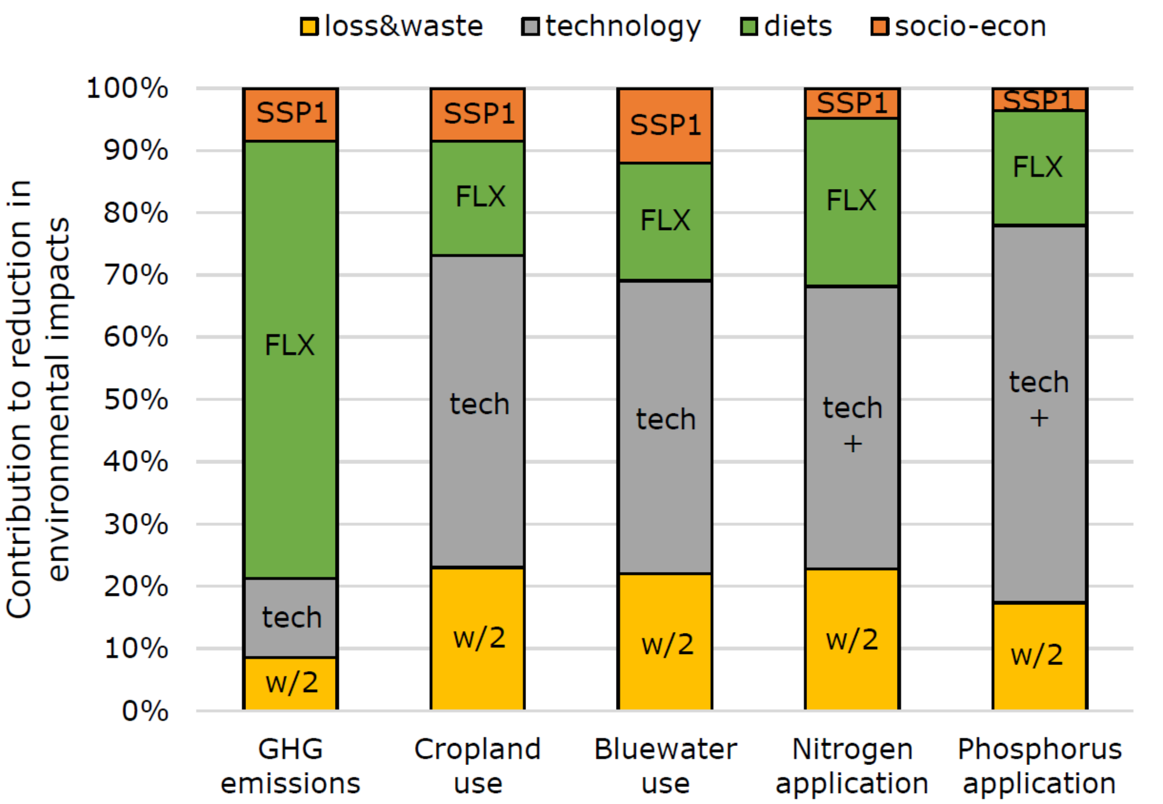

Figure 4. Combination and relative contribution of mitigation measures that simultaneously stay below the mean values of the planetary-boundary range. The mitigation measures include different levels of technological improvements for each

environmental domain [measures of high ambition (*tech+*) for nitrogen and phosphorus application, and measures of medium ambition (*tech*) for GHG emissions, and cropland and bluewater use]. The other measures cannot be differentiated by domain, and include a halving of food loss and waste (*waste/2*), changes towards more plant-based, flexitarian diets (*FLX*), and optimistic socio-economic development with higher income and lower population growth (*SSP1*) than currently expected. A middle-of-the-road development pathway is also feasible when combined with more ambitious reductions in food loss and waste (*waste/4*) (see Figure 3).

Methods

Food systems 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, e.g. 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 parameterised 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 [56].

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 [57], 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 [58] and livestock [38]. Non-CO_2 emissions of fish and seafood were calculated based on feed requirements and feed-related emissions of aquaculture [59], and on projections of the ratio between wild-caught and farmed fish production [60,61]. Our baseline emissions estimate agrees well with existing ones that follow the same methodology [1,62].

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 coproducts (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 [59] and projections of the ratio between wild-caught and farmed fish production [60,61] 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 [63]. 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, atmospheric deposition, minus nitrogen offtake by crops [22,43,64] (Supplementary Information). The results of the sensitivity analysis are reported in Extended Data Figure 3.

Scenarios 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. For estimating the environmental impacts in absence of dedicated mitigation measures (a scenario we term baseline projection), we paired footprints of current intensity to future projections of food demand along several socio-economic 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) [65–67]. 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.[66]

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 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 Sustainable Development Goals for 2030. In the ambitious scenarios (*waste/4*), we assumed reductions in food loss and waste of 75%, which is likely close to the maximum value that can be theoretical avoided [30].

The scenarios of technological change (*tech*, *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 [68]. 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 USD/tCO_2 (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 USD/tCO_2-eq) 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 current yields and yields that are feasible in a given agro-climatic zone [32]. The potential efficiency gains in nitrogen and phosphorus application rates included rebalancing of fertilizer application rates between over and under-applying regions in line with closing yield gaps [32]. In the ambitious technology scenario (*tech+*), we increased yield-gap closures to 90% based on data by Mueller and colleagues [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 of 50% [7]. 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 for soybeans which are assessed on a more conservative basis by Mueller and colleagues than by the IMPACT team.

The scenarios of dietary change include shifts towards diets in line with global dietary guidelines (*HGD*), as well as more specialised, but nutritionally balanced dietary patterns. For the former, we followed suggestions to limit the intake of red meat to below 300 g per week [69], the intake of added sugar to below 5% of total energy intake (about 31 g/d) [70], consume five portions (400 g/d) or more of fruits and vegetables [36], and 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 5-year age groups [71], something that can be seen as an upper bound. Calorie needs reach a maximum of 2500 kcal/d for ages 19-25 (averaged between men and women), but are reduced to 2000 kcal for ages 66 and older. The average calorie needs differed by region based on its age composition, and ranged around 2100 kcal/d. In a sensitivity analysis, we only implemented changes in dietary composition 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 the current evidence on healthy eating (Extended Data Table 5, Supplementary Table 2) [37,46,72]. The flexitarian diets (*FLX*) included at least 500 g/d of fruits and vegetables of different colours and groups (the composition of which is determined by regional preferences), at least 100 g/d of plant-based protein sources (legumes, soybeans, nuts), modest amounts of animal-based proteins, such as poultry, fish, milk, and eggs, and limited amounts of red meat (1 portion per week), refined sugar (<5% of total energy), vegetable oils that are high in saturated fat (in particular palm oil), and starchy foods which have 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, etc) and fruits (temperate, tropical).

Planetary boundaries

The planetary-boundary framework attempts to define a safe operating space for humanity characterised by a stable Earth system [10–12]. Above planetary boundaries, it is suggested that ecosystem processes are at risk of becoming destabilised [11,12]. For contextualising 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 degrees Celsius (RCP2.6), which we derived from a model comparison of three integrated assessment models [57] normalised to the marker scenario of the associated emissions pathway [62]. The resulting budget of 4.7 (4.3-5.3) $GtCO_2$-eq focuses on the non-CO_2 emissions related to agriculture (methane and nitrous oxide), which is in line with previous assessments [57] 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, e.g. through deforestation and carbon sequestration in soils [73]. How those flows should be balanced vis-à-vis the emissions from other sectors, and how additional pressure from land-based CO_2 sequestration contribute or counteract other sustainability targets and planetary boundaries are an important question for future research.

Large uncertainties exist as to what an appropriate planetary boundary for land use should be [12]. Based on an analysis of forest biomes, Steffen and colleagues [12] suggested a boundary value in line with maintaining (not increasing pressure on) current forest cover. Such a target is in line with the strongly correlated target for biosphere integrity if non-agricultural land is placed under protection of biodiversity-compatible land use [12,74,75]. Because our modelling framework explicitly tracks cropland use, we translate the suggested target to a value of keeping current cropland use at 12.6 (10.6-14.6) Mkm^2 based on our own model calculations using the IMPACT model [33]. Desirable for future work would be 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, urbanisation, and other socio-economic 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, the 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, 1100-4500) [20], which includes the other suggested values in its uncertainty range [12,76]. 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 (780-3,190) km^3 of bluewater used in agriculture. We note that uncertainties persist both about the concrete assumptions on environmental flow requirements [12,77], as well as about which methodology would be best suited [78].

To inform the boundary value for reactive nitrogen, De Vries and colleagues [19] calculated global risk values for eutrophication based on region-specific estimates of current nitrogen concentration in runoff and concentrations that would stay below ecological and toxicological thresholds of inorganic N pollution. The original boundary value for nitrogen was calculated by multiplying the global risk value by an estimate of current anthropogenic N fixation (fertilizer use + fixation by crops) [19]. Here we apply the risk values to N 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, atmospheric deposition, minus nitrogen offtake by crops) as a control variable in a sensitivity analysis (Extended Data Figure 3). The resulting estimate of 52-69 TgN per year (67-90 TgN when using N surplus as control) might be considered conservative, because de Vries and colleagues kept regions that currently apply less than the critical load of nitrogen at that value, which in some cases can be significantly lower than needed from an environmental and food-security perspective [79]. For that reason, we adopted an upper boundary value in line with a scenario that balanced N application between over and under-applying regions and closed yield gaps to 75% [32], which yielded a final boundary value of 69 (52-113) TgN of nitrogen application from fertilizers (90, 67-146 TgN of nitrogen surplus).

In contrast to nitrogen, phosphorus can build up in the soil and is washed out as runoff 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. De Vries developed a global phosphorus-flow model focused on added P assuming steady-state surface pools, critical P concentrations to prevent eutrophication of 50-100 mg P/l and flexible recycling rates (Extended Data Figure 2, Supplementary Information). Under no-waste recycling, the long-term P boundary amounted to 6-12 TgP per year, and it increased to 8-16 TgP per year assuming a recycling rate of 50%. In line with our focus on scenarios of change, we adopted the latter values. Similar to nitrogen, there are great regional imbalances of phosphorus application [80], so we again infer an upper tolerable value from a scenario that rebalanced P application between over and under-applying regions and closed yield gaps to 75% [32]. The resulting internally derived phosphorus boundary is 16 (8-17) TgP of phosphorus application.

Data availability

The data that support the findings of this study are available from the Oxford University Research Archive (ORA) with the identifier doi:10.5287/bodleian:yJoX495Eg. Additional data are available upon request.

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Legends for Extended Data Items

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 theoretical 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].
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) [35,36,69,70].
FLX	Dietary shifts towards more plant-based, flexitarian dietary patterns based on recent evidence on healthy eating [37,45,72] 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.

Extended Data Table 1. Scenarios of change in food loss and waste (waste/2, waste/4), technological change (tech, tech+), and dietary change (HGD, FLX).

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

Extended Data Table 2. Global food production (Mt) in 2010 and 2050 by food group and step along the food chain. Steps include consumption (*cons*), food waste at the household level (*waste*), food loss at production (*loss*), industrial and other demand for agricultural products (*other*), 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*).

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

Extended Data Table 3. Environmental footprints of food commodities (per kg of product). 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.

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

Extended Data Table 4. Reduction in environmental footprints (%) due to technological changes by food group. Technological changes include changes of medium ambition (*tech*) and changes of high ambition (*tech+*). Zero entries indicate where no data was available to infer potential improvements, and for pelagic fish reflect a production method (marine fishing) that does not require feed inputs.

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)				

Extended Data Table 5. Food-based dietary recommendations for healthy, more plant-based (flexitarian) diets. The recommendations include recommended minimum (min) and maximum (max) intake expressed by weight or calories, and servings. Fish and seafood can be substituted by plant-based foods (legumes, soybeans, nuts and seeds, fruits and vegetables) in vegetarian diets.

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

Extended Data Table 6. Decomposition of impacts of dietary scenarios. Impacts (shows 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 the current evidence on healthy eating.

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 [81].	Food-related GHG emissions in line with limiting global warming to below 2 degrees Celsius [62] with uncertainty derived from a model comparison of integrated assessment models [57].	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 [76].	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.

Extended Data Table 7. Planetary boundaries of the food system, including motivation, method of estimation, and suggested boundary range.

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

Extended Data Figure 3. Planetary option space related to different control variables of nitrogen and yield-related feedbacks. 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 feedbacks 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).