Ambitious food system interventions required to mitigate the risk of exceeding Earth's environmental limits

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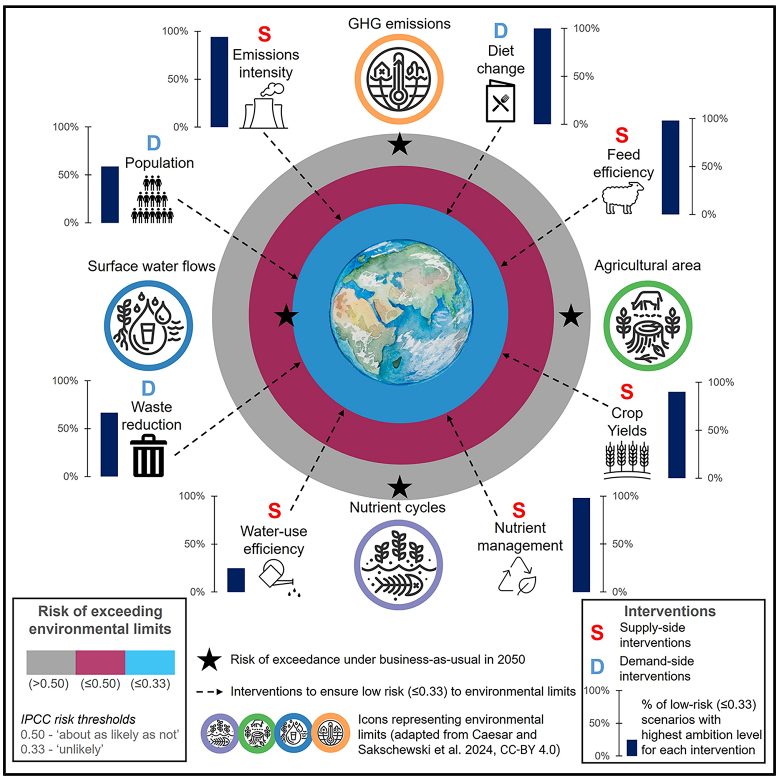
Graphical abstract



Highlights

- Only a few intervention combinations are compatible with all environmental limits
- GHG emissions and nutrient cycles are the hardest environmental limits to mitigate
- Diet change, GHG intensity, nutrient management, and feed efficiency are key levers
- Ambitious policy actions are needed to enable food system intervention combinations

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In brief

Transforming the global food system is crucial to staying within Earth's environmental limits. Studies assessing the efficacy of interventions to reduce the environmental impact of the food system rely on differing models and worldviews. We synthesize previous research to develop a novel risk assessment framework to estimate the risk mitigation potential of thousands of possible intervention combinations against key environmental limits by 2050. Our findings emphasize the importance of ambitious food-system action to ensure unlikely exceedance of all environmental limits.

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Ambitious food system interventions required to mitigate the risk of exceeding Earth's environmental limits

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SCIENCE FOR SOCIETY The global food system is a key driver of environmental change. Current trends in food production and consumption present an unacceptable risk to exceeding environmental limits. A transformation of the global food system is needed to keep the Earth within a safe operating space. Previous studies have used differing food system models to assess the efficacy of behavioral and technological interventions to mitigate environmental impact. However, there has not been a systematic analysis of intervention efficacy that can control for differences in methods and model assumptions.
Here, we synthesize previous studies to provide a foundation for a novel risk assessment framework that estimates the risk mitigation potential of numerous intervention combinations against four key environmental limits by 2050. Our findings underline the necessity of ambitious action to enable the necessary intervention combinations. We suggest that feasibility assessments of policy actions across different geographic and socioeconomic contexts should be a research priority.

SUMMARY

Transforming the global food system is essential to avoid exceeding Earth's environmental limits. A robust evidence base is crucial to assess the scale and combination of interventions required for a sustainable transformation. We developed a risk assessment framework, underpinned by an evidence synthesis of global food system modeling studies, to quantify the potential of individual and combined interventions to mitigate the risk of exceeding global environmental limits for agricultural area, greenhouse gas (GHG) emissions, surface water flows, and nutrient cycles by 2050. GHG emissions and nutrient cycles are the most difficult limits to avoid exceeding and are conditional on shifts toward diets with a low proportion of animal-source foods; steep reductions in emissions intensity; substantial improvements in nutrient management, feed-conversion ratios, and crop yields; and efforts to limit overconsumption and food waste. Ambitious actions across the global food system are needed to ensure the required level of risk mitigation.

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INTRODUCTION

The global food system is pushing environmental indicators that define the Earth's biophysically safe operating space into and beyond a zone of uncertainty,[1–4] with potentially serious repercussions for the environment and human development.[5,6] Business-as-usual (BAU) scenarios of global food production and consumption to 2050 are almost certain to exceed several planetary boundaries,[7–12] and it is widely acknowledged that a transformation of the global food system is required to avoid transgressing these environmental limits. With attention focusing on interventions (mitigation options) that can facilitate this transformation,[13–17] a comprehensive and integrated assessment of the scale and combination of interventions that can keep the Earth system within environmental limits is urgently required to support policy making and catalyze on-ground action.

Over the past decade, global studies have presented many scenarios and estimates of the environmental benefits of a range of demand-side and supply-side food system interventions. However, the outputs and conclusions are sensitive to several analytical choices, including the modeling paradigm, input data and model parameterization, scenario specification, type and scale (or ambition) of interventions assessed, and the environmental indicators used.[18–20] These choices are influenced by study aims and researcher worldviews,[21,22] leading to bias and gaps in our understanding of the environmental impacts of food system trajectories and the effectiveness of interventions. The recent criticism[23] of the United Nations Food and Agriculture Organization's (FAO's) 1.5°C roadmap,[24] which found a low mitigation potential for dietary change (at odds with recent studies[12,25,26]), demonstrates how preferential data and scenario choices could potentially misinform policy. Intercomparisons of land-use change[18,20,27,28] and selective reviews of other environmental indicators[15,29,30] highlight the considerable range in estimates across studies. A systematic analysis of global food system modeling studies that can control for differences in methods and model assumptions and synthesize the mitigation potential of a comprehensive suite of interventions, is therefore needed.

The thresholds that define global environmental limits (such as planetary boundaries or Earth system boundaries) are often set conservatively to avoid exceeding biophysical tipping points[1,2,4,5,31] and include a zone of uncertainty that accounts

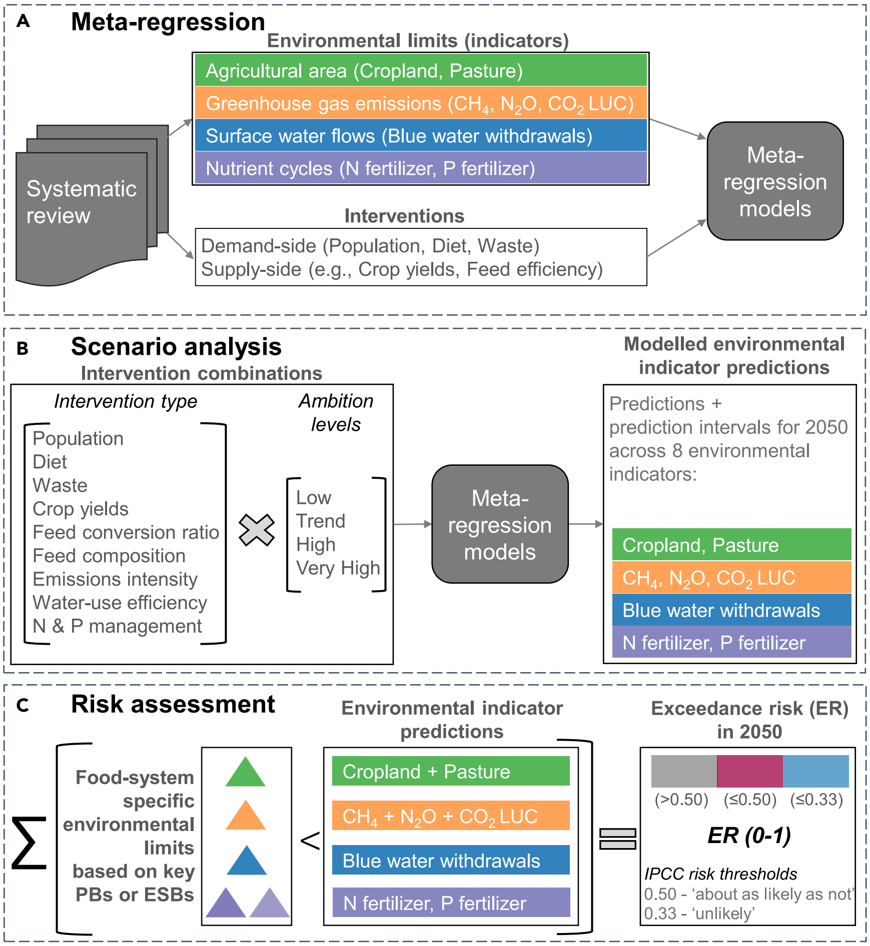

Figure 1. Intervention modeling and risk assessment framework

A simplified illustration of the three main stages of the analysis.

(A) Linear mixed-effects meta-regression models for eight environmental indicators corresponding to four key environmental limits (agricultural area, GHG emissions, surface water flows, nutrient flows), and intervention-related variables extracted from selected studies.

(B) Database with mean predictions and prediction intervals for each of the eight environmental indicators comprising all relevant intervention combinations (Table 1).

(C) Exceedance risk calculation combining environmental limit PDFs (Table 2; see also Table S2; Figure S3) and meta-regression model prediction intervals. PB, planetary boundary; ESB, Earth system boundary; LUC, land use change; N, nitrogen; P, phosphorus. For the N and P cycles, risk estimates were calculated separately and then averaged to derive a nutrient-cycle risk metric.

for incomplete scientific knowledge and variability in Earth system functioning.[32,33] The share of this safe operating space available to the food system is also uncertain and dependent upon assumptions about the environmental impacts of other sectors.[7,8] Given these uncertainties, a risk assessment framework that reflects the latest scientific consensus can enhance the evaluation of food system interventions by determining the probability, or risk, of exceeding environmental limits.

Here, we present a synthesis of global food system modeling studies. Our quantitative analysis is underpinned by an input database with thousands of scenario projections from 26 systematically selected studies to identify the effects of various interventions and the combinations that keep the Earth's system within a safe operating space by 2050. We developed a quantitative risk assessment framework underpinned by a suite of statistical meta-regression models that estimate the risk mitigation potential of major food system interventions relating to four global environmental limits: agricultural area, greenhouse gas (GHG) emissions, surface water flows, and nutrient cycles. These are defined by the latest consensus on global environmental limits, notably research on planetary boundaries (PBs)[4] and Earth system boundaries (ESBs).[5] We finally complemented the quantitative analysis with a qualitative review of a broader set of 64 studies to identify real-world actions that could enable the modeled interventions. Our synthesis delivers comprehensive risk mitigation estimates for individual interventions and explores intervention combinations and key actions that can help move the food system within environmental limits.

RESULTS

Synthesizing available evidence and quantifying risk

We systematically reviewed modeling studies of the global food system published in academic journals and major international reports since the year 2000, with environmental impact estimates up to and including 2050. Out of the 1,688 studies originally identified, we used a robust protocol to select 64 for further qualitative and quantitative synthesis (Note S1, Figure S1). For the quantitative analysis, we assembled a harmonized dataset[34] of projected future food system impacts for eight environmental indicators that relate to four key environmental limits (Note S2), based on a subset of 26 studies that met strict data inclusion and completeness criteria (Figure 1A; methods; Note S3).

Food system modeling studies typically construct a BAU scenario that follows historical trends in food demand and agricultural productivity.[19] Intervention scenarios range from marginal to substantial deviations from the BAU,[35] based on a range of supply-side (i.e., technology or practices that improve production efficiency) and demand-side (i.e., changes in food demand or its composition) interventions that can reduce environmental

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Table 1. Food-system-specific environmental limits for selected environmental indicators in 2050

Indicator (sub-indicator)	Abbreviation	Environmental limit best estimate (low–high estimate)	Relevant global PB or ESB	Short description
Sum of the area of all arable land and land under permanent crops	Cropland	<3.31 (3.20–5.46) billion ha	Land-system change	Total land area under agriculture (cropland + pasture) adjusted for possible pathways in non-agricultural uses (mining, infrastructure, and urban expansion), compatible with the 54%–75% (3,466–4,790 Mha) global forest cover requirement across major forest biomes (tropical, temperate, boreal)[2,4]
Area under permanent meadows and pastures	Pasture			
Total agricultural area (i.e., cropland + pasture)	*TotalAgArea*			
Direct on-farm CH_4 emissions	CH_4	–	Climate change	Total agriculture emissions (direct CH_4 + N_2O + net CO_2 emissions from land use and land-use change) in line with the published range of estimates of agriculture's share of the global carbon budget in vetted IPCC AR6 scenarios consistent with staying within 2.0°C and 1.5°C[37,42]
Direct on-farm N_2O emissions	N_2O	–		
Land-use change CO_2 emissions	CO_2LUC	–		
Direct GHG emissions from agriculture (i.e., CH_4 + N_2O + CO_2)	*NonCO$_2$+LUC*	<2.67 (−3.87 – 11.0) Gt CO_2e yr^{-1}		
Water withdrawals (surface water and groundwater) by agriculture	*Water*	<4,400 (1,033–8,558) km^3 yr^{-1}	Surface water flows	Total blue-water withdrawals in agriculture adjusted for possible pathways in water demand across other economic sectors and relative future contributions of surface water and groundwater.[43] Safe withdrawal limits were computed as globally aggregated environmental flow requirements based on flow alterations no greater than 15% (10%–20%) for maintaining moderate to high levels of ecological protection in riverine ecosystems[5,44]
Total synthetic nitrogen fertilizer application in agriculture	*N_{fert}*	<69 (52–113) Tg N yr^{-1}	Nutrient cycles: Nitrogen	Safe thresholds for N_{fert}, and P_{fert} based on the latest consensus in global environmental limits.[4,5,8] The N_{fert} limits exclude biological fixation as per Springmann et al.[8] A cumulative Nutrients boundary was not calculated due to the non-additive nature of the individual indicators. Instead, risk estimates were averaged across indicators to derive risk metrics
Total mined phosphorus fertilizer application in agriculture	*P_{fert}*	<16.0 (6.0–17.0) Tg P yr^{-1}	Nutrient cycles: Phosphorus	

The table shows the best estimate (mode), lower bound (minimum), and upper bound (maximum) for each environmental limit. In italics are the indicators used to assess risk against the food-system-specific share of the relevant planetary boundary (PB) or Earth system boundary (ESB). In the case of agricultural area and GHG emissions, the indicators are calculated as the sum of two or more sub-indicators. For detailed methodology and full list of data sources see also Note S2; Table S2.

impacts (methods; Note S3).[36–41] Typically, studies either assess just a single intervention or scenario narratives integrating multiple interventions, such as the shared socioeconomic pathways (SSPs).[20,28] This makes it difficult to untangle the effect size of each intervention, and the intervention scale and combinations are limited to those encompassed in integrated storylines instead of spanning the entire range of possible futures.

To enable a quantitative synthesis of food system interventions, we identified eight key environmental indicators representing the four critical environmental limits of agricultural area, GHG emissions, surface water flows, and nutrient flows (Table 1; Note S2). We then established a set of robust and consistent quantitative variables that could be used to determine the effect of each major intervention (Table 2; Note S3). We used the compiled data from the selected food system models to fit linear mixed-effects meta-regression models for each of the environmental indicators, with interventions modeled as composite fixed effects predictor variables, and with the effect size

Table 2. Intervention levels and combinations

Interventions	Level of mitigation ambition: Low	Trend	High	Very high	Units	*Description*. Mitigation action example	Relevant limits
Demand side							
Population	10.1	9.66	9.5	9.1	billion people	*Global human population in 2050 according to the latest median estimate by the United Nations*[45] *and the range across SSP 3.0 scenarios.*[46] This intervention could be enabled through reducing fertility rates via promoting education and reproductive health services.[41,47]	All
Diet						*Global daily average calorie intake from ruminant meat, dairy, and monogastric products (pork, chicken, eggs, and farmed seafood) and plant calorie intake per person (excluding waste).* Changes in diet could be enabled through promoting diet change toward plant-based diets and reduced overconsumption of animal and plant calories in high-income countries via market-based incentives, e.g., taxes, and/or awareness campaigns such as pro-environmental dietary guidelines.[40] All combinations between animal and plant calories are modeled *ceteris paribus* and guarantee a minimum intake of 2145 kcal cap^{-1} day^{-1} that meets minimum dietary energy requirements for healthy populations with body mass index values between 18.5 and 24.9[8] (see Table S9). Values > 2,400 kcal cap^{-1} day^{-1} are considered representative of overconsumption in predominantly sedentary high-income populations.[48] The studies used for quantitative analysis considered a diversity of plant calories in line with current global averages or regional food-based dietary guidelines.[49] We therefore did not explicitly consider micronutrient adequacy except for vitamin B_{12} which can only be sourced naturally through ASFs.[50] All modeled diets satisfy the World Health Organization's recommended intake of 2.4 μg day^{-1} for adults and adolescents[51] (see Table S10)	
Animal calories	Rich	BAU	Low meat	Low ASF	kcal cap^{-1} day^{-1}		All
Ruminant meat	65	50	40	25			
Dairy	170	150	160	115			
Monogastric	320	260	230	145			
Plant calories	2,350	2,185	2,020	1,860	kcal cap^{-1} day^{-1}		
Waste	25	0	−25	−50	%Δ	*Change in household and retail waste across all food categories (meat, dairy, seafood, cereals, pulses, fruit, and vegetables) relative to 2010*. Reduction in household and service waste could be achieved through education and awareness campaigns or reductions of serving sizes[52] (see Table S11)	All
Supply side							
Crop yields	15	30	45	60	%Δ	*Global weighted yield increase per unit area for all crops relative to 2010.* Crop yields could be increased via breeding and genetic technologies, agronomic practices optimized to local climatic and soil conditions, and enhanced nutrient management (e.g., precision agriculture)[53]	All
FCR					kg DM/kg output	*Global weighted average animal FCRs for different livestock systems (ruminant meat, dairy, and monogastrics).* Reductions in FCRs corresponding to increased feed efficiency can be achieved through developments in animal breeding and nutrition[54] (see Table S12).	All
Ruminant meat	35	30	25	20			
Dairy	2	1.75	1.5	1.25			
Monogastric	4	3.5	3.0	2.5			

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Table 2. *Continued*

Interventions		Level of mitigation ambition: Low	Trend	High	Very high	Units	*Description*. Mitigation action example	Relevant limits
Feed composition						% FCF	*Share of FCF* (i.e., *crops and fodder produced on land that could otherwise produce human food) in livestock feed by livestock type (ruminant meat, dairy, and monogastrics)*. This two-way intervention interacts with FCRs and its direction depends on study worldview (Table S7) as it can involve either increasing the amount of feed from ecological leftovers (i.e., grass, food waste, by-products) and/or the use of degraded/abandoned land,[22] or intensification of livestock production in feedlots to increase feed efficiency (see Table S13)	All
Ruminant meat		5	10	15	20			
Dairy		15	20	25	30			
Monogastric		80	85	90	95			
GHG emission intensity	EI_{CH4}	0	13	26	40	%Δ	*Global reduction in non-CO_2 (CH_4 and N_2O) GHG emission intensity (emissions per unit of food produced) relative to 2010.* This can involve shifts toward agricultural practices that minimize emissions from soils and rice production, improved manure management, and feed supplements to reduce enteric fermentation in ruminants[55]	GHG emissions
	EI_{N2O}	0	4	8	12	%Δ		
	carbon price	0	25	100	200	US$2,010 t CO_2eq^{-1}	*Carbon price effects on net CO_2 emissions from agricultural land use.* Relevant actions triggered by an increase in carbon price include avoided deforestation, regrowth and reforestation, and soil carbon farming practices[14,36]	
Water-use efficiency		0	5	10	15	%Δ	*Increase in crop yield relative to the volume of water withdrawn (in kg of crop relative to blue-water withdrawals in m^3) across all crops (including animal feed) relative to base year (2010) levels.* Increases can be achieved through crop breeding and selection, soil-water conservation practices that improve the productive capacity of soil, and precision irrigation techniques[56,57]	Surface water flows
N&P management								
Nutrient-use efficiency	NUE_N	0	10	20	30	%Δ	*Increase in the amount of nitrogen (NUE_N) and phosphorus (NUE_P) uptake by crops as a proportion of the total amount of N and P fertilizer applied, respectively, relative to 2010.* Higher NUEs could be achieved through better nutrient management (e.g., optimizing fertilizer selection, timing, application) and regulation of application rates.[58] For N the very high setting corresponds to an increase from a global 2010 average NUE_N of 0.46[59] to 0.60 by 2050. For P this corresponds to a change from 0.67[10,60] to 0.78 in 2050	Nutrient cycles
	NUE_P	0	5	10	15	%Δ		
Nutrient recycling	N	0	10	20	30	%	*The proportion of synthetic nitrogen or mined phosphorus fertilizer offset through recycling of agricultural and human waste streams.* This intervention follows the formulation in[8,61] and entails improvements in infrastructure (pit latrines, septic tanks, enhanced sewage systems) to enable the recycling of nutrients from agriculture (manure and crop residues) and human waste (household waste and sewage)[58,60]	
	P	0	15	30	45	%		

The table includes the levels of mitigation ambition for each intervention with examples of mitigation actions, as synthesized from selected studies (see supplemental data[34] for full list of actions). Relevant environmental limits are those where we assume an intervention to have a significant impact. Trend refers to a BAU trajectory that follows historical or expected trends. See also Note S4 and Tables S8–S13 for detailed justification of the chosen mitigation ambition levels across each intervention. ASF, animal-source foods; DM, dry matter; FCF, food-competing feed; EI, GHG intensity; NUE, nutrient-use efficiency.

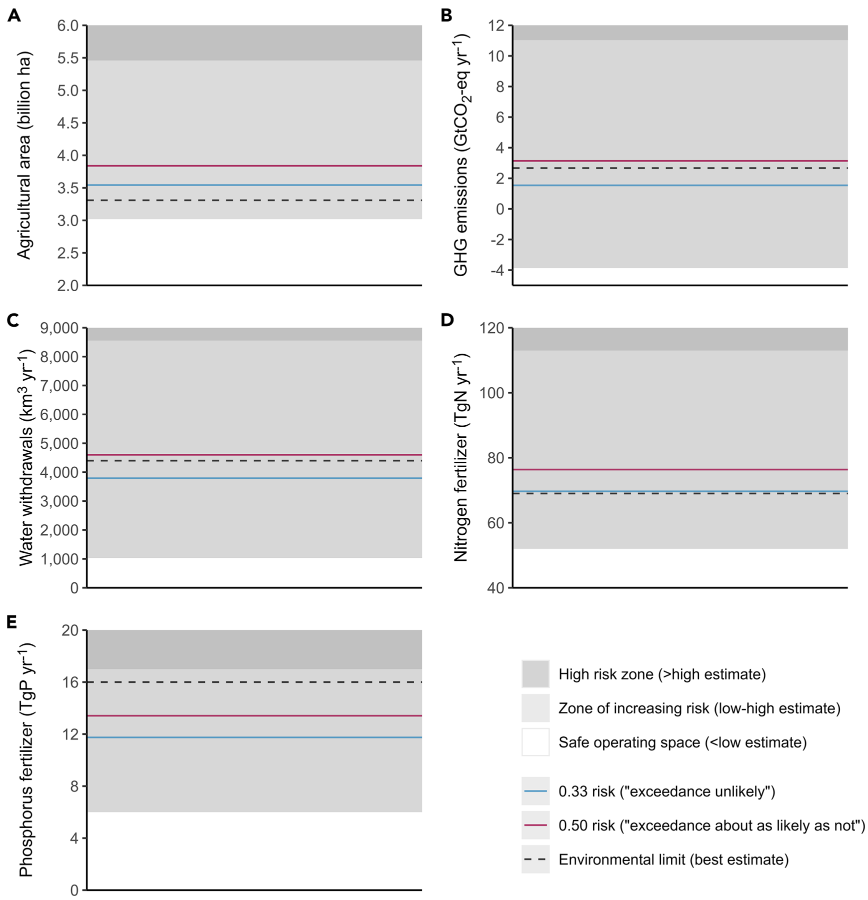

Figure 2. Critical risk thresholds and risk zones for each environmental indicator/limit in 2050

The shaded areas represent the different risk zones following terminology consistent with planetary boundaries.[2,4] Blue and red horizontal lines represent two IPCC risk thresholds (0.33 and 0.50), and the dashed black line is the best estimate (mode) of the environmental limit (see Table 1).

(A) Risk thresholds and risk zones for agricultural area.

(B) Risk thresholds and risk zones for GHG emissions.

(C) Risk thresholds and risk zones for water withdrawals.

(D) Risk thresholds and risk zones for nitrogen fertilizer.

(E) Risk thresholds and risk zones for phosphorus fertilizer.

(environmental impact relative to the base year) as the dependent variable (Note S4). We established four levels of mitigation ambition (low, trend or BAU, high, and very-high) for each intervention for 2050 through a review of the range in mitigation ambition seen in reviewed studies and other recent literature carried out by co-author groups with expertise in a particular intervention. The low and very-high mitigation ambition settings were bounded by values considered in the literature, while the trend represented the average expectation based on historical trends and high represented an intermediate level of ambition between trend and very-high (Table 2; methods; Note S4). Using the meta-regression models, we generated predictions for all combinations of relevant intervention levels against each environmental indicator for 2050 (Figure 1B). Following a sensitivity analysis protocol,[20] we used our prediction database to compute individual effects for each intervention level relative to the overall trend (i.e., a BAU trajectory where all interventions are set at trend level).

We then defined triangular probability density functions (PDFs) capturing the best estimate and uncertainty zone for each environmental limit (Tables 1 and S2). Following principles of probabilistic risk assessment,[62] the risk of exceeding relevant limits for each modeled indicator prediction was calculated by comparing Gaussian distributions drawn from modeled prediction intervals against PDFs of environmental limits (Figures 1C and S3). By pooling risk estimates for all environmental limits, we then identified combinations of intervention levels that remained below two critical Intergovernmental Panel on Climate Change (IPCC) risk thresholds for describing quantified uncertainty[63,64]: <0.50 risk (exceedance about as likely as not) and <0.33 risk (exceedance unlikely) (methods; Note S4). As our approach did not consider how potential transgressions of any given environmental limit could affect the risk status of the other limits through predominantly amplifying interactions,[4,33] our pooled risk estimates should be seen as conservative.

The location of key risk thresholds differs by indicator and risk level

The shapes of triangular PDFs of environmental limits in 2050 reflect the level of uncertainty around minimum and maximum estimates (Table 1; Note S2). This impacts the location of different risk thresholds in relation to the best estimate (Figure 2). While previous research[8,52] implicitly considers values below the best estimate as representative of a more acceptable level of risk, depending on the nature of the distribution, the best estimate may still entail an elevated level of risk relative to one or both critical IPCC risk thresholds (0.33 and 0.50). For example, in the case of agricultural area (Figure 2A), a distribution with a mode (best) estimate (3.31 billion ha) very close to the minimum (3.20 billion ha) means that both the 0.50 and 0.33 risk thresholds are substantially higher than the best estimate. The opposite is the case for phosphorus (Figure 2E), where the mode (best) estimate of 16

Tg P yr^{-1} is close to the maximum (17 Tg P yr^{-1}), and is therefore higher than both risk thresholds. In the cases of GHG emissions (Figure 2B) and water withdrawals (Figure 2C) where the triangular distribution is more symmetric, the best estimate lies in between the two risk thresholds, while for nitrogen (Figure 2D) the best estimate directly overlaps with the 0.33 risk threshold. Probabilistic risk assessment encompassing the uncertainty zone for each environmental limit (as illustrated in Figure 2), highlights that ensuring unlikely exceedance (<0.33) across several indicators may entail a level of acceptable risk that is significantly below the current best estimate of the environmental limit.

Mitigation potential of individual food system interventions

We present modeled predictions of mitigation potential for individual interventions set at different levels of mitigation ambition relative to the overall trend (all interventions set at trend level) in 2050 (Figure 3; see Figure S4 for sub-indicator results). To illustrate the results in the sections below, we concentrate on the mean maximum mitigation potential (very-high relative to the overall trend) expressed as a percentage reduction relative to the overall trend prediction and as reduced pressure in physical units.

Demand-side interventions show significant mitigation potential across all indicators

Demand-side interventions show high mitigation potential across all indicators, with some variability depending on the indicator (Figure 3). Shifting to diets with a low proportion of animal-source food (ASF) (very-high ambition) could achieve the maximum risk reduction across agricultural area (−24.0%; −1.26 billion ha) and GHG emissions (−47.4%; −5.77 $GtCO_2eq$), reflecting reduced demand for pasture and feed crops and reduced GHG emissions from enteric fermentation (Figure S4). A low-ASF diet also shows considerable mitigation potential for water withdrawals (−14.2%; −550 km^3) and nutrient flows (−11.4% N_{fert}, −10.8% P_{fert}; −15.0 Tg N_{fert}, −2.48 Tg P_{fert}). Other demand-side interventions also result in substantial mitigation potential across all indicators, especially for GHG emissions (−10.3%; −1.25 $GtCO_2eq$ for population interventions) and nutrient flows (−12.2% N_{fert}, −11.0% P_{fert}; −16.0 Tg N_{fert}, −2.52 Tg P_{fert} for plant calorie reduction) (Figure 3).

Among supply-side interventions, improvements to feed conversion ratios (FCRs) have the highest overall mitigation potential across all indicators, with an especially strong effect on agricultural area (−17.7%; −0.93 billion ha) and GHG emissions (−33.6%; −4.09 $GtCO_2eq$) owing to substantially reduced feed demand from both cropland and pasture (Figures 3 and S4). Targeted interventions such as water-use efficiency (WUE), reductions in emissions intensity, and N&P management, show considerable mitigation potential for each of the relevant indicators. Unlike GHG emissions and agricultural area, supply-side interventions such as improved N&P management show much higher mitigation potential for nutrient flows (−39.2% N_{fert}, −41.5% P_{fert}; −51.7 Tg N_{fert}, −9.52 Tg P_{fert}) due to their strong influence on improving nutrient-use efficiency (NUE) and recycling. Improvements in WUE have a slightly lower effect compared to a low-ASF diet on water withdrawals (−11.1%; −430 km^3).

Some supply-side interventions exhibit trade-offs across certain indicators

Actions to increase crop yields and change feed composition have trade-offs for some indicators (Figure 3). Higher (+60%, very-high ambition) crop yields have considerable mitigation potential for agricultural area (−7.6%; −0.40 billion ha) and associated GHG emissions (−10.4%; −1.26 $GtCO_2eq$) because of avoided cropland expansion and forest regrowth substantially outweighing the increase in N_2O emissions from additional fertilization (Figure S4). However, higher crop yields could slightly increase water withdrawals (+0.8%; +30 km^3) and nutrient flows (+4.3% N_{fert}, +4.1% P_{fert}; +5.70 Tg N_{fert}, +0.94 Tg P_{fert}). In the absence of any concomitant FCR improvements, a higher grain percentage in livestock feed would have a modest mitigation potential for agricultural area (−3.4%; −0.18 billion ha), with pasture reduction (−0.32 billion ha) offsetting the necessary increase in cropland (+0.14 billion ha). A similar effect is observed for GHG emissions (−1.5%; −0.18 $GtCO_2eq$), where negative emissions from pasture abandonment would offset any increases from cropland expansion and additional fertilization (Figure S4). However, this would entail substantial increases in water withdrawals (+11.8%; +460 km^3) and nutrient flows (+9.4% N_{fert}, +8.4% P_{fert}; +12.4 Tg N_{fert}, +1.92 Tg P_{fert}) from additional inputs (Figures 3 and S4).

Only a few intervention combinations achieve risk reduction below safe thresholds

While interventions such as reducing animal calories, improved FCRs, and N&P management show considerable mitigation potential (Figure 3), no single intervention is sufficient to stay below both critical risk thresholds for all four environmental limits. Here, we mapped the performance of all modeled predictions against their risk mitigation and intervention ambition level to generate a complete set of 1,048,576 possible intervention combinations (Table S15; Figure S5). We then queried this combination set to identify combinations that met the critical risk thresholds of 0.50 (exceedance about as likely as not) and 0.33 risk (exceedance unlikely) individually for each environmental limit and then combined across all limits (Figures 4 and S6–S9).

While 80.3% of all possible combinations meet the 0.33 risk threshold for global surface water flows, the safe operating space is considerably more restricted for agricultural area (11.5% of all modeled combinations), nutrient cycles (10.2%), and GHG emissions (0.8%), with slightly higher numbers of scenarios meeting the 0.50 threshold (Figures 4A and S6–S9). Only 0.81% (n = 8,244) of all combinations satisfy the 0.50 risk threshold across all environmental limits, with an even smaller subset of 0.02% (n = 204) combinations achieving the 0.33 risk threshold (Figure 4). This finding reflects the interplay of synergies, trade-offs, and dependencies arising from different interventions and ambition levels and their respective efficacy across different environmental limits.

Focusing on the intervention combinations that meet risk thresholds across all environmental limits reveals the required ambition levels for each intervention (Figure 4B). Over 97%, 80%, and 70% of combinations that meet either of the risk thresholds entail very-high ambition levels for animal calories, N&P management, and FCRs, respectively (Figure 4B). Crop yields, plant calories (reduced overconsumption), waste, and emissions intensity are the next most influential intervention group, with

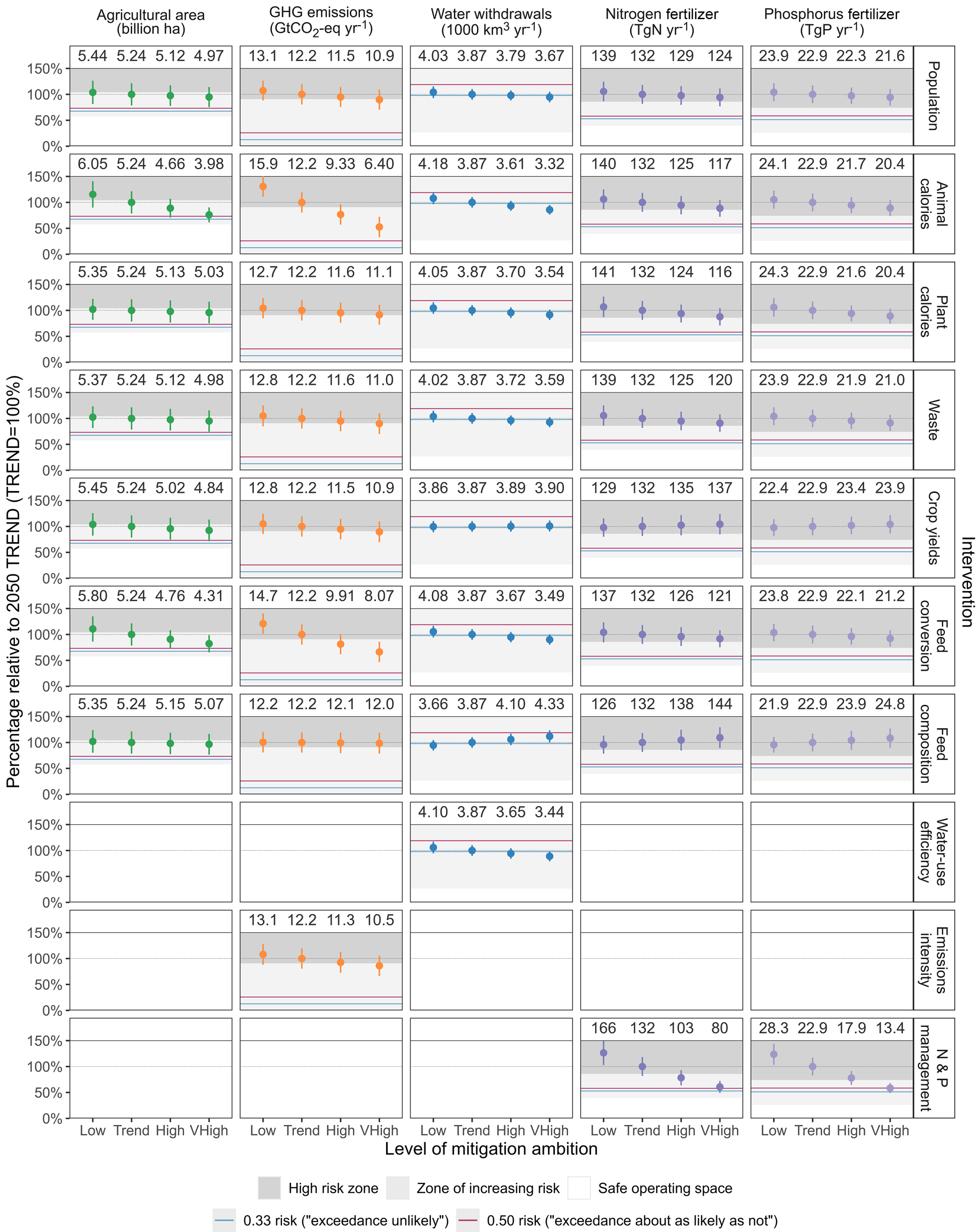

Figure 3. Modeled mitigation potential in 2050 under a range of ambition levels for selected interventions

Each panel shown presents percentage impact relative to the 2050 overall trend (all interventions set at trend level) for a specific level of mitigation ambition (*x* axis) of a selected intervention (facet rows) across each of the environmental indicators (see Table 1). Data are presented as mean predictions (bubbles) and 95% bootstrap prediction intervals (vertical lines). Black numbers at the top of panels indicate pressure in physical units (e.g., billion ha for agricultural area). Shaded areas represent the different risk zones following terminology consistent with planetary boundaries.[2,4] Blue and red horizontal lines represent the two IPCC risk thresholds (0.33 and 0.50). Empty panels correspond to interventions excluded from individual models due to lack of relevance or missing/insufficient data. See also Note S7 (Table S24; Figure S4) for sub-indicator results and supplemental data[34] for source data.

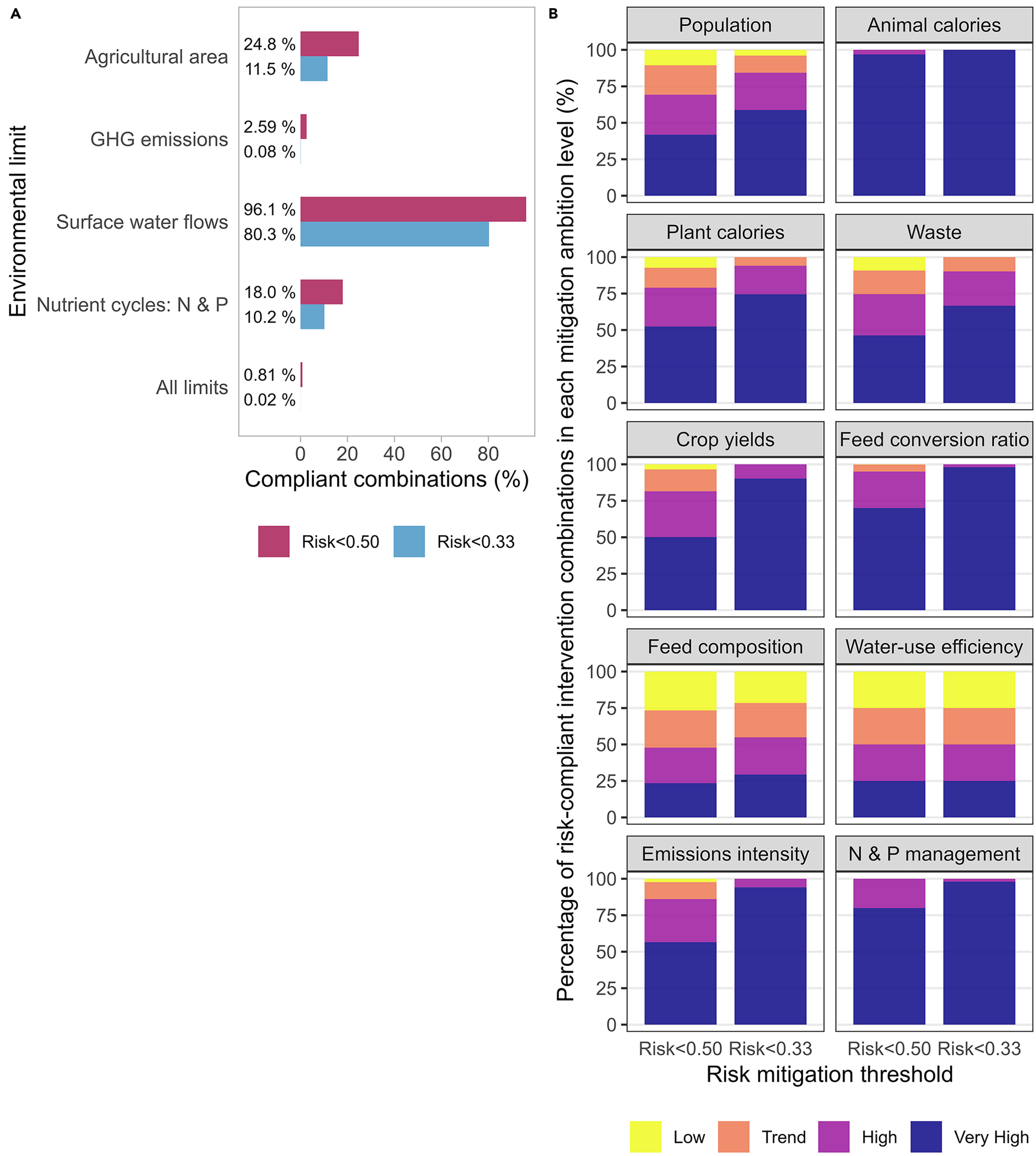

Figure 4. Percentages of risk-compliant combinations and required intervention ambition levels to meet alternative risk thresholds across all environmental limits

(A) The horizontal bar plot displays the percentage out of a total of 1,048,576 possible intervention combinations that meet each of the two risk thresholds (risk < 0.50 and risk < 0.33) for each environmental limit and combined for all limits.

(B) The vertical bar plots display the percentages of each of the four levels (low, trend, high, very-high) of mitigation ambition for the intervention combinations that meet each of the two risk thresholds for all environmental limits. See also Note S7 (Figures S6–S9) for indicator-specific results and supplemental data[34] for source data.

Table 3. Mitigation actions discussed in reviewed studies mapped to relevant interventions

		Interventions									
		Demand-side			Supply-side						
Scope	Action categories (examples)	Population	Diet	Waste (inc. loss)	Crop yields	Feed conversion	Feed composition	GHG intensity	Water-use efficiency	Nutrient-use efficiency	Nutrient recycling
Farm-level	Advanced agronomic technologies (e.g., precision farming)				■			■	■	■	
Farm-level	Advanced crop production techniques (e.g., hydroponics)				■			■	■	■	
Farm-level	Agronomic conservation practices (e.g., minimum/no till)				■			■	■	■	■
Farm-level	Biochar addition to soil							■			
Farm-level	Bioenergy crop cultivation on degraded or abandoned land							■			
Farm-level	Enhanced nutrient management strategies				■			■		■	■
Farm-level	Fine-tuning feed composition to improve digestibility					■	■	■		■	
Farm-level	Genetic modification (e.g., higher-yielding crops/animals)				■	■		■	■	■	
Farm-level	Globally optimized cropland use (shifting to efficient areas)				■						
Farm-level	Improved agronomic management (e.g., timing of sowing)				■			■	■	■	
Farm-level	Improved irrigation efficiency (e.g., drip irrigation)								■		
Farm-level	Improved sewage systems (e.g., separate urine collection)										■
Farm-level	Improved water management techniques				■				■		
Farm-level	Increased fertilizer use in under-yielding countries				■			■		■	
Farm-level	Integration of biogas plants and manure storages							■			■
Farm-level	Livestock herd management (e.g., short rotation grazing)					■	■	■		■	■
Farm-level	Locally appropriate crops (e.g., climate-resilient cultivars)				■				■	■	
Farm-level	Nitrification and urease inhibitors							■		■	
Farm-level	Nutrient recovery (e.g., use of crop residuals and manure)				■		■	■		■	■
Farm-level	Reduction in crop feed (e.g., use of grass and by-products)					■	■	■		■	
Farm-level	Shifting livestock production to dairy/monogastrics					■	■	■			
Farm-level	Slow-release fertilizers and fertigation									■	
Farm-level	Transition towards fodder-based livestock production					■	■	■			
Farm-level	Veterinary health measures for livestock (e.g., vaccination)					■		■		■	
Processing & Retail	Circular supply chain designs to recycle food waste			■							■
Processing & Retail	Digital infrastructure (e.g., internet and GSM coverage)			■							
Processing & Retail	Food preservation practices that reduce spoilage			■							
Processing & Retail	Improved cold-chain infrastructure			■							
Processing & Retail	Improved inventory management and purchasing			■							
Processing & Retail	Improved packaging for extended shelf life			■							
Processing & Retail	Improved transportation, processing, and storage facilities			■							
Processing & Retail	Recovery and redistribution of surplus food (e.g., in retail)			■							
Consumers	Dietary guidelines for healthy and sustainable diets		■	■							
Consumers	Education and awareness campaigns		■	■							
Consumers	Family planning (e.g., education and empowerment)	■	■								
Consumers	Food labeling regulations with sustainability scoring		■	■							
Consumers	Integrating sustainability in social protection programmes		■	■							
Consumers	Market-based instruments (e.g., carbon price, health tax)		■	■	■	■	■	■	■	■	■
Consumers	Novel protein sources (e.g., algae, mycoprotein, insects)		■								
Consumers	Nudges towards plant-based diets (e.g., reward schemes)		■	■							
Consumers	Nutrition counselling in maternal/childcare programmes		■								
Consumers	Promotion of more sustainable diets in gastronomy		■	■							
Consumers	Public procurement (e.g., meals in schools and hospitality)		■	■							
Consumers	Transforming food environments (e.g., sustainable snacks)		■								
Agricultural policy	Access to affordable credit (e.g., co-operative banks)				■	■		■	■	■	
Agricultural policy	Climate policies strongly linked to agricultural strategies		■			■	■	■		■	
Agricultural policy	Enabling farmers to make long-term investments			■	■	■	■	■	■	■	■
Agricultural policy	Enhanced market access (e.g., better rural infrastructure)			■	■						
Agricultural policy	Establishment of productivity standards and targets			■	■	■	■	■	■	■	■
Agricultural policy	Improved access to pollination services				■						
Agricultural policy	Policies to regulate agricultural runoff									■	
Agricultural policy	Optimizing the location of production of commodities				■	■		■	■	■	
Agricultural policy	Payment for ecosystem services							■			
Agricultural policy	Strict regulation and basin limits on extraction/application								■	■	■
R&D	Increased investment in research, technology, innovation		■	■	■	■	■	■	■	■	■
R&D	International working groups on sustainable consumption		■	■							
R&D	Technical assistance and capacity building		■	■	■	■	■	■	■	■	■
R&D	Technology and knowledge transfer		■	■	■	■	■	■	■	■	■

(continued on next page)

Table 3. *Continued*

The table provides a non-exhaustive list of 58 actions with examples across the food system, as qualitatively mentioned in the 64 systematically selected studies. Gray cells indicate that an action has the potential to contribute to an intervention but are not intended to be indicative of the strength of association between actions and interventions. Blank cells indicate a low potential association or no relationship between an action and an intervention. Scope coverage follows supply-chain stages (i.e., farm level, processing and retail, consumers, agricultural policy, R&D) previously defined in Poore and Nemecek.[65] Actions are listed alphabetically within each scope category. For further details and tallying of actions against solutions, see supplemental data.[34]

around 50% and over 70% of combinations requiring very-high ambition levels to meet the 0.50 and 0.33 thresholds, respectively (Figure 4B). Population is slightly less critical, with 40% and 59% of combinations that meet the 0.50 and 0.33 risk threshold, respectively, requiring a very-high level of ambition. Overall, the majority (>75%) of combinations compliant with the stricter 0.33 risk threshold require very-high ambition levels across key demand-side (animal calories and plant calories) and supply-side (crop yields, FCRs, emissions intensity, N&P management) interventions, highlighting their critical risk mitigation potential.

For the two remaining supply-side interventions (feed composition and WUE), there is a broader range of ambition levels that achieve risk thresholds (Figure 4A). For feed composition, high to very-high ambition, indicative of more grain-dependent livestock systems, features in only 48% and 55% of combinations compliant with the 0.50 and 0.33 risk threshold, respectively. The reason for lower percentages of high ambition levels is the mixed effect feed composition has across different indicators at the global level, with livestock intensification able to reduce agricultural area and GHG emissions but also associated with increased water and nutrients requirements (Figure 3). Despite its considerable mitigation potential for surface water flows (Figures 3 and S8), WUE does not appear to play a role in the selection of overall low-risk combinations, reflecting the sufficient risk mitigation potential from more universally effective interventions (e.g., demand-side interventions) and the safer global status of the surface water flow limit.

Diverse actions can enable risk-compliant intervention combinations

The option space of intervention combinations that would enable the food system to stay within all environmental limits is narrow (Figure 4). Despite the significant feasibility challenges, highly ambitious mitigation levels remain within reach—provided the numerous and diverse opportunities for action across the food system are fully and promptly exploited. Based on the qualitative synthesis of the 64 systematically selected studies, we identified key on-ground actions at different stages of the food supply chain that could enable the level of mitigation ambition required across demand- and supply-side interventions (Table 3).

Opportunities and challenges for achieving the required demand-side intervention levels

A major challenge to achieving the required levels of demand-side mitigation is the feasibility of implementing transformative global-scale actions within the available time frame.[13,55] The required levels of mitigation by 2050 across diets, waste, and population are at odds with current patterns in high-income countries,[66] the continued growth of the global middle class with associated increases in ASF consumption,[26,41] and trends in food waste[67,68] and population growth.[41,69] However, increasing social awareness of the environmental mitigation potential of demand-side actions and their co-benefits with health and well-being,[31,39,40] coupled with emerging options[13] to overcome systemic financial and political challenges,[55] could, under the right policy settings, counter current trends. While demand-side actions tend to focus on consumer behavior, the broader economic and regulatory environment (Table 3) will need to evolve substantially to unlock technological innovation and the changes in choice infrastructure necessary for shifting consumer behavior.

The adoption of low-ASF diets with significantly less ruminant meat[52] is critical. The pace of the nutrition transition[66] shows that equally rapid shifts toward low-ASF diets could be realizable with the right policy settings and retail environments.[70] This includes consumer-centered actions such as incorporating sustainability into dietary guidelines and food labels, education campaigns on sustainable diets, investment in healthier food environments, and pricing that reflects negative environmental and health externalities (Table 3). Promoting legumes, nuts, and seeds in high-income countries can reduce environmental risk while improving health outcomes.[52] Novel protein alternatives (e.g., plant-based or lab-grown substitutes, mycoprotein, and insects) could catalyze dietary shifts away from animal protein with potential environmental and health co-benefits,[71,72] but their micronutrient content and broader social and economic implications warrant further consideration.[73–75] More equitable income distribution could facilitate dietary transitions.[40] Actions tailored to specific country contexts, underpinned by global monitoring efforts such as the Food Systems Countdown Initiative,[76] could target behavioral feasibility challenges such as established social norms favoring meat consumption.[77] Studies that dynamically account for changes in diets in response to changing social norms suggest that the low-ASF diet is achievable by 2050.[78,79]

Similar actions could support a reduction in overconsumption and food waste, and therefore in plant calories, especially in upper- and middle-income countries where excess energy intake contributes to overweight and obesity.[55,66] Changes in sociocultural norms toward healthier diets can reduce excess plant calories (particularly from processed carbohydrates and vegetable oils) and food waste.[66,80] Effective interventions for reducing food waste include reductions in the size and type of servings in hospitality settings, changing nutritional guidelines in schools, and information campaigns.[81] These need to be accompanied by complementary actions in the food retail environment such as improvements in food packaging and inventory management (Table 3). Reliable and consistent food waste data are also of critical importance in informing national food waste strategies aspiring to an ambitious 50% reduction target, with some encouraging signs of progress in this respect.[68,82]

The significance of slowing population growth is often downplayed in food system studies.[41,69] Actions that could limit global population to 9.1 billion in 2050 include education to change social norms around family planning, empowering women, and reducing gender and other inequalities.[31,47] Such measures could support sustainable diet transitions by addressing the combined negative effects of population growth and the nutrition transition.[41,66] More equitable redistribution of wealth through policies addressing inequalities in income and gender, and stronger linkages between climate, health, and agriculture policy portfolios, could also help achieve the necessary mitigation ambition across all demand-side interventions (Table 3).

Opportunities and challenges for achieving the required supply-side intervention levels

Equally ambitious actions are needed to achieve the required levels of supply-side mitigation. While the portfolio of proposed actions relies on technologies and management practices that increase the efficiency of food production at the farm scale, the broader policy, regulation, and research and development (R&D) context can accelerate innovation and knowledge transfer across different geographic regions (Table 3).

Key actions to achieve the modeled gains in feed efficiency include better animal breeding and husbandry, improving feed digestibility through improved feed composition and supplements, and optimizing grazing management (Table 3). The overall feed conversion efficiency of the food system is also tied to the protein composition in the diet. For example, protein from aquaculture or meat alternatives generally has a higher conversion efficiency compared to that from terrestrial livestock.[71,83,84]While shifting to more grain-based livestock production can improve FCRs, it could increase demand for food-competing feed (FCF). Livestock systems that implement feed circularity[85] through the use of low-opportunity-cost biomass such as crop by-products,[86] food waste, and pasture[85] can reduce FCF demand (Table 3) but can only provide a limited amount of animal protein due to their more extensive nature.[87,88] This implies a contingency with a low-ASF diet.[89]

Reducing non-CO_2 emission intensities by the required level would entail better feeding practices and supplements to reduce enteric fermentation,[90] in addition to improvements in housing systems, manure storage, and nutrient and residue management in cropland soils and rice paddies[14,37,55] (Table 3). A carbon price is an established market-based mechanism to incentivize these actions and to also reduce land clearing and promote CO_2 sequestration through trees and soil enhancement.[37] The modeled carbon price of US\$200 tCO_2eq^{-1} is considered feasible by 2050 and offers significant technical mitigation potential—especially in South America and Africa.[37]

A crop yield increase of 60% by 2050 relative to 2010 is assumed in combinations that meet the 0.33 risk threshold. An expected 30% increase follows historical (1970–2010) trends for cereal crops,[53] with an observed ~18% increase already achieved between 2010 and 2022.[91] Additional yield increases are possible through further investment and technology transfer in improved management practices, advanced agronomic (e.g., precision farming) and genetic (e.g., higher-yielding and climate-resilient) technologies, and additional fertilization in areas with high yield gaps,[52,55] (Table 3). However, climate change could compromise yield gains in some crop-growing regions.[92,93]

Increasing global WUE by 5%–15% requires additional investments in crop production techniques and technologies to those that can increase crop yields, including soil-water conservation and improved water management (e.g., rainwater harvesting, higher yields from rainfed agriculture, and deficit irrigation) (Table 3). The assumed WUE gains remain feasible given the plethora of actions available in different geographic contexts.[9,56] However, translating gains in WUE to actual water savings relies on robust water accounting, stricter enforcement of caps to prevent water misuse and misallocation, and a better understanding of behavioral responses of irrigators to increases in WUE.[57]

Attaining the required levels of N&P management requires enhanced nutrient management across the food system. This includes actions to increase NUE such as better placement and timing of fertilizers; precision irrigation; integrated weed, pest, and disease management; enhanced manure storage and spreading methods; and enhanced recycling of animal manures,[58] along with soil-conservation practices (e.g., cover crops, tillage management, buffer strips) to minimize erosion and runoff[60] (Table 3). Recycling P from wastewater is currently more established,[94] with few technologies able to maximize both N and P recovery at once.[95]

DISCUSSION

Low-risk food system pathways must target key interventions

We find that unlikely exceedance (<0.33 risk) across all environmental limits in 2050 is contingent on the highest level of mitigation ambition for key interventions, namely animal calories, N&P management, FCRs, and GHG emissions intensity. Strong efforts are also required to increase crop yields and to limit plant calories, food waste, and population growth. Low-risk intervention combinations are also reflective of the significant challenge of reducing risk to below 0.33 for the GHG-emissions and nutrient-cycle limits, with both already in a high-risk state.[4,5,31]

Our synthesis strongly supports a growing body of high-profile studies[7,8,12,25,26,52] that highlight diets low in ASFs as a key prerequisite for the food system to remain within environmental limits. This contradicts recent FAO reports[24,96] that downplay the role of diet change without explicit quantification of the environmental benefits of alternative interventions.[23] More broadly, our findings underline the central role of demand-side interventions. A key challenge that follows is how to turn around the slow progress to date in necessary actions (Table 3). Many interventions, including dietary change and waste reduction, are usually modeled as exogenous drivers, without adequate consideration of local biophysical constraints, affordability and sociocultural norms—all of which must be overcome to reach a societal tipping point that enables large-scale transitions in food consumption.[16,97–99]

The urgency of critical supply-side interventions such as reducing GHG intensity and improving nutrient management through technological innovation and agricultural practices is well established.[14,100] So too is the importance of increasing crop yields, as seen in consistent investment and gains in recent decades,[15,91] despite persistently high yield gaps in some regions. Our findings also emphasize the critical role of feed efficiency. Beyond its significant methane reduction potential,[54,90,101,102] most studies did not explicitly consider feed efficiency interventions or their interactions with feed composition and/or alternative diets (Table S8), although several authors acknowledge their importance (Table 3). Our findings are at odds with the Dublin Declaration, which advocates for maintaining or increasing livestock numbers through agroecology.[103] However, agroecological systems have lower feed efficiencies and must be paired with diets low in ASFs.[89,104] Since low-risk food system pathways require low-ASF diets and high feed efficiencies, actions that enable shifts away from ruminants toward animal products with higher feed efficiencies (e.g., aquaculture, poultry and eggs) and promote more affordable and palatable plant-based and novel protein sources are likely to be more effective in reducing environmental impacts. Additional actions may also be necessary to minimize any negative trade-offs for animal and human health in intensive livestock systems.[105]

Target setting and risk assessment of food systems

Explicit target setting, such as a proposed "net zero" equivalent target for the food system,[106] could accelerate transformative action. Equally ambitious targets are necessary for all environmental indicators,[3,107,108] and broader Sustainable Development Goal indicators—especially those intrinsically linked to the food system, such as food and nutrition security, animal and human welfare,[105] and livelihoods.[109,110] While some mitigation actions are likely to show considerable co-benefits, others, especially those that require high R&D investment, could entail significant costs to producers and consumers, with potentially adverse impacts on food security.[14,55] While our risk assessment focuses on system-level risk metrics, sub-indicator results show that certain interventions can have disparate effects (e.g., between cropland and pasture, or between different GHGs) that may also warrant shorter-term targets. For example, the 45% methane reduction target by 2030 recommended in UNEP's Global Methane Assessment[111] reflects methane's role as a short-lived but potent climate pollutant. Similar interim targets for other indicators can inform appropriate actions. Risk assessment frameworks such as the one developed here can then be used to synthesize available evidence from multiple sources using a simple actionable metric to identify optimal intervention portfolios that meet such targets.

Interactions across Earth system processes are complex and amplifying, and safeguarding all environmental limits is therefore essential.[1,2,6,31] The presence of significant regional risk thresholds, such as in the case of nutrient cycles[100] and water,[5,9,112] highlights the importance of setting environmental limits and targets at different levels, from global to sub-national (e.g., at basin level). Our risk estimates do not encompass all environmental limits and their potential interactions[4,33,113] and do not explicitly account for regional or seasonal exceedances.[9,94] Interventions such as WUE are likely to be extremely important in the context of local environmental limits, despite the relatively low level of global risk.[5] Additional interventions that achieve spatially optimized outcomes[114,115] may also be required to ensure adherence to both global and local environmental limits.

Our risk assessment framework does not explicitly consider or quantify feasibility challenges.[13,77] Many studies focus on a limited combination of highly ambitious best-case interventions, raising concerns around feasibility.[77,116,117] While our approach includes thousands of intervention combinations, food system models must better incorporate feasibility evaluation[16,77,118] to allow more realistic comparisons of different ambition levels across multiple interventions based on technological, economic, sociocultural, and institutional barriers to identify optimum action pathways. Feasibility assessment (including true-cost accounting[119]) of interventions and their possible combinations and adaptability across different geographic regions and socioeconomic contexts is an important topic for further investigation.[16,120] Furthermore, while our risk estimates capture the spread in intervention effect size across underlying models, our approach does not capture how specific underlying actions could influence the environmental performance of a given intervention. For example, crop yields could increase in response to gains in total factor productivity[47] or, alternatively, through additional irrigation and fertilization inputs, with each of these underlying actions having different environmental implications. Different actions and mechanisms of implementation have diverse synergies or trade-offs across environmental indicators and may also entail divergent implementation challenges.[13,99] Future research could refine our qualitative mapping of actions and interventions (Table 3) to extract quantitative effect sizes at the level of individual actions. This could involve a series of regional or national level syntheses focusing on key food system actions, sustainability indicators, and feasibility or adaptability challenges.

Toward improved syntheses of food system interventions

Despite the large number of scenarios to ensure comprehensive coverage of the option space, we assume partial or full implementation of interventions without accounting for alternative implementation pathways in the period leading up to 2050. Our statistical models implicitly draw on the diverse pathways and intervention trajectories assumed in the underlying studies. However, studies underline the importance of the timing and pace of implementation,[7,25] especially for climate change where the remaining carbon budget also depends on decarbonization trajectories in other key sectors such as energy and transport.[12,37] Dynamic process-based models consider non-linearities and saturation effects in intervention effectiveness associated with trends in technology and consumer behavior,[40,78,84] as well regional heterogeneity in key food demand drivers (e.g., population, income, and agricultural R&D) and their interactions with food prices.[121] While our statistical approach encompasses the range in responses to interventions across underlying models (many of which exhibit non-linearities), it implicitly assumes linearities in the assumed environmental response to any given intervention. Future syntheses could more systematically compare non-linearities in implementation using timeseries multi-model ensembles based on diverse scenario narratives. Improved data sharing and harmonization of scenarios and intervention parameters, in a similar fashion to IPCC climate mitigation scenarios,[37,42] would greatly facilitate future syntheses. Recent developments include a new generation of multi-model target-seeking scenarios that incorporate diverse and coherent sustainability perspectives such as the sustainable development pathways.[108]

Our work provides the most comprehensive synthesis and risk assessment to date on the mitigation potential of possible food system intervention combinations for 2050. Our findings reiterate the urgency of ambitious levels of action on both the

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demand and supply side of global food systems to give humanity the best chance of remaining within environmental limits. While we consider many possible futures, there are potentially many more intervention combinations than those identified that meet risk thresholds. This includes values in between or beyond the four levels of ambition considered across each intervention, as well as additional interventions not explicitly considered in our analysis. For example, given the considerable risk mitigation potential of diet shifts and their inherent feasibility challenges,[15,25,26] the emergence of novel protein alternatives[72] or other future technologies[13] could expand the option space by accelerating sustainable dietary transitions. Food system models are only just starting to explicitly incorporate dynamics between technology and diet change.[22,75,84] Future research needs to comprehensively synthesize the risk mitigation potential of available interventions and the numerous actions available to enable them across different contexts.

METHODS

Systematic review and input dataset compilation

We carried out a systematic literature search for scenario modeling studies of global food system sustainability following the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) protocol.[122,123] We developed a universal search string refined using an article test list of 20 highly cited articles. We then used this search string to search across four major academic databases (ProQuest, Scopus, Web of Science, Science Direct) to identify peer-reviewed journal articles and book chapters that contained quantitative scenario projections of global environmental impacts explicitly associated with food production for the year 2050 (Note S1; Figure S1). We complemented our academic literature search with a comprehensive search of the gray literature, focusing on key reports from major food-related organizations (FAO, World Bank, CGIAR, IFPRI, WRI, UNEP, UNCCD) using the Google search engine. The initial search was carried out in November 2017, with periodic updates through search engine alerts (ProQuest, Scopus, Web of Science, and Google Scholar) up to and including November 2024. We also ran an updated systematic search with a slightly modified search string in early December 2024 to ensure that any literature published since the initial search had been captured (Table S1). For details of all search strings, exclusion criteria, and all search results and study screening, see Note S1 and Hadjikakou.[34]

A total of 1,688 titles and abstracts were screened and, following reference scanning ("snowballing") and search alerts and co-author suggestions, 191 full texts were assessed for inclusion. From these, 64 studies met all inclusion criteria for qualitative synthesis and were also shortlisted for quantitative synthesis (Note S1; Figure S1). Following data extraction from each publication (including supplemental information or code), and data directly obtained from the lead authors of each study, we developed a comprehensive input database[34] of published global food system model scenarios with impact estimates and interventions for eight commonly used environmental indicators related to four key environmental limits (Note S2). Based on the available data, we settled on four demand-side and six supply-side interventions. Demand-side interventions include a range of sociocultural and technological changes that can decrease or alter aggregate food demand, namely a slowdown in the population growth rate, shifts toward more plant-based diets, and reductions in food waste.[38–41] Supply-side interventions include improved farm management, increased efficiency (e.g., yield gap closure in crop and livestock systems), and technological advances that reduce resource-use intensity and emissions.[36,37]

Following strict exclusion criteria (Table S5), we created a harmonized dataset from 26 studies with recent and consistent base year values (Table S6) and variable specification representing 2,246 future scenario projections and 946 scenario narratives and assembled a full dataset of input parameters that contained the minimum set of 29 quantitative variables necessary to parameterize all interventions (Note S3; Table S4). At this stage, we also excluded any environmental impacts associated with changes in demand for biofuels, non-food crops, and marine fisheries (Figure S2). For our analysis, we considered only environmental impacts associated with terrestrial crop and livestock systems and inputs to aquaculture. The resulting dataset was used to train the meta-regression models (see below). This follows van Dijk et al.,[124] who only included studies that could be harmonized in their quantitative analysis. Study authors who contributed significantly to the data compilation and harmonization effort were invited to become co-authors.

Defining food-system-specific environmental limits

We defined food-system-specific environmental limits for four Earth system processes for the year 2050 based on the latest scientific consensus on global environmental limits and other literature (Table 1; Note S2). We selected eight environmental indicators and specified environmental limits based on available model outputs in the literature as well as on current scientific consensus around environmental limits.[4,5] Uncertainty in environmental limits was incorporated by specifying triangular PDFs, commonly used in risk analysis,[125] characterized by best estimate, minimum, and maximum values. Where a best estimate was not available, we used the mode value calculated as $3 \times \text{mean}(x)\text{-min}(x)\text{-max}(x)$, to allow the fitting of a triangular distribution. For GHG emissions, we used data from the AR6 Scenarios Database v1.1,[42] which contained 260 scenarios with total direct emissions from agriculture (CH_4 + N_2O + net CO_2 emissions from land use and land-use change) compatible with a 67% and 50% chance of remaining within 2.0°C and 1.5°C, respectively (Table S2).[37]

Environmental limits for the food system account for possible trajectories in relevant non-food sectors, which also exert a significant pressure on each of the limits (Table 1; Note S2). The PDF representing the environmental limit for GHG emissions drawn from the AR6 Scenarios Database already encompassed assumptions around the decarbonization trajectories in other key sectors such as energy and transport. Nutrient-cycle limits for N and P fertilizer were already specific to agriculture.[4,5,8] For the agricultural area limit, we considered the range in possible deforestation trajectories for reasons other than agricultural expansion,[126,127] while, for the surface water flows limit, we considered the range in non-agricultural water demand (i.e., from households and industry) as well as the relative contributions of surface water and groundwater[43] (Tables 1 and S2).

Our environmental-limit PDFs therefore encompassed both the inherent uncertainty in defining the Earth system's safe operating space as well as the range of possible trajectories of relevant non-food sectors and share of each environmental limit available to the food system in 2050 (Note S2).

Meta-regression modeling and intervention effect size

Following data extraction, study selection, and extensive harmonization of data inputs (Note S3), we used the curated dataset of scenario projections assembled from the 26 selected studies (Table S3) to fit linear mixed-effects meta-regression models[124,128] for each environmental indicator. We then used the fitted statistical models to generate a comprehensive database of predictions for 2050. We tested both a random slope and random intercept model design with the model version used in each study as the random effect term to reduce the bias resulting from large differences in the number of published scenarios between studies and controlled for the lack of independence between scenarios within each study or studies using similar runs from the same food system model.[124,128] We fitted eight linear mixed-effects models (LMMs), one for each environmental indicator using a restricted maximum-likelihood routine implemented in the R package lme4.[129]

We used the log response ratio of environmental impact computed as ln (future estimate/base year estimate) as the response variable. An exception was made for pasture, where we used percentage change as the response variable (as seen in van Dijk et al.[124]), and CO_2 LUC (see below). The independent variables representing relevant demand- and supply-side interventions for each environmental indicator were parameterized as composite variables and fixed-effect regressors to emulate biophysical processes in the original models (Note S6). We pre-processed independent variables to control for differences in starting values by harmonizing units and calculating multipliers relative to the base year (for population, diet, crop yields, FCRs, emissions intensity, WUE, and NUE), absolute percentages (for waste, feed composition, and nutrient recycling), and absolute values (for carbon price). For CO_2 LUC, the data compiled from the selected studies (see supplemental data[34]) was not sufficiently comparable in scope to allow harmonized predictions compatible with the AR6 Scenarios Database.[42] We instead trained an LMM using 2203 vetted 2010–2050 observations in the AR6 Scenarios Database[42] with the land-system model as the random effect term, 5-year averaged annual CO_2 LUC emissions from agriculture as the dependent variable and carbon price, year, and 5-year averaged annual change in cropland and pasture as independent variables (Notes S4 and S5).

We carried out model selection and validated prediction accuracy through cross-validation, following best practice for predictive models.[130] We used repeated cross-validation, repeating the cross-validation five times with alternative fold numbers (over the range 3:*k*, where *k* was the number of random factors minus 1), implemented in the R package cvms,[131] which explicitly controls for the random effect structure in LMMs. We formulated and tested alternative model structures based on a process-based logic that replicates model structures of selected studies using aggregates of independent predictors (e.g., total feed demand for ruminant meat) (Notes S4 and S5). We selected models based on the root-mean-square metric for further analysis. We used variance inflation factors to test for collinearity and likelihood-ratio tests to further refine the selection of fixed-effect predictors. During this stage, we also tested the addition of an initial condition delta as per Alexander et al.,[18] which improved the fit for the cropland, water withdrawals, methane, nitrous oxide, and N_{fert} models. Further tests and outlier handling were performed to exclude any bias in the model coefficients due to violations in the homogeneity of residual variance or influence from outliers in the models using the robustlmm[132] and LMERConvenienceFunctions[133] packages (see Note S4). The final selection of models was guided by marginal (i.e., variance explained by fixed effects) and conditional (i.e., variance explained by fixed and random effects) R^2 estimates calculated using the R package MuMIn[134] following the method by Nakagawa and Schielzeth.[135] Selected models had cross-validated marginal and conditional R^2 values above 0.64 and 0.79 respectively, reflecting the high percentage of overall variance explained by all LMMs (Table S14). See Tables S16–S23 for individual model summaries.

We established four levels of mitigation ambition (low, trend, high, very high) through an extensive review of the modeled range within the systematically selected studies or across other recent studies identified by co-authors with expertise in each intervention. We ensured that the very-high mitigation ambition level did not exceed the level of ambition previously modeled by other studies while also dismissing values we considered to be infeasible for a given intervention (see Note S4 and Tables S8–S13 for detailed justification for each ambition level). As an example, the low-ASF diet (very-high ambition level for animal calories) was based on the EAT-Lancet diet,[52] while ruminant meat FCRs range from the current global average (low) to that achieved in efficient grassfed systems like Australia and New Zealand. In the case of population, we drew on recent population projections.[45,46]

We then generated predictions using the fitted LMMs encompassing combinations between all relevant interventions at each level of mitigation ambition (Figure 1B; Table 1). Mean predictions and prediction intervals were calculated using a simulation function in the R package merTools[136] that draws a sampling distribution for random and fixed effects and then estimates the fitted value across that distribution, providing an efficient approximation to a parametric bootstrap. We used 2,000 samples to calculate the 95% prediction interval around the mean, incorporating uncertainty of random and fixed effects, as well as residual variance from the model. We averaged the prediction intervals to derive normal distributions for each prediction. Predictions in log response ratios were converted to percentage change and multiplied by 2010 base-year values (Table S24) to derive estimates in absolute units for 2050. To compute effect sizes for different interventions levels, we calculated intervention-level averages by summarizing (mean and standard deviation) mitigation potential for each intervention level across each indicator (Figures 3 and S4) based on a one-at-a-time sensitivity approach previously used in Stehfest et al.[20]

Risk assessment and analysis of risk-compliant intervention combinations

Mean predictions of the impact of interventions across each of the eight environmental indicators were used to calculate the risk of exceedance of environmental limits for all combinations

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of interventions and levels of ambition (i.e., predictor variables) (Figure 1; Note S4). Combining uncertainty in both the predictive models and the environmental limit PDF, the risk of exceedance was calculated as:

$$ER_{i,j} = P\left(Y_{i,j} > X_j\right)$$

where Y is the normal distribution of the modeled prediction interval for each intervention combination i and indicator j, and X is the PDF of the environmental limit (agricultural area, GHG emissions, surface water flows, and one each for the two nutrient cycle indicators, N_{fert} and P_{fert}).

To identify intervention combinations that met IPCC-calibrated uncertainty risk thresholds,[64] we mapped the performance of all intervention combinations against their risk mitigation and ambition level. We did this individually, for each of the four environmental limits, and combined across all limits, yielding a total of 1,048,576 intervention-level combinations across environmental limits. We then selected the scenarios that met the <0.50 risk (exceedance about as likely as not) and <0.33 risk (exceedance unlikely) thresholds compatible with the calibrated uncertainty language applied by the IPCC in its assessments.[63,64] We finally analyzed the selected intervention combinations to identify the option space available in terms of the type and level of ambition of interventions required to reduce the risk of exceedance to below each of the two risk thresholds.

Limitations of the study

Our modeled intervention levels (low, trend, high, very high) are representative of the range of ambition within the selected studies but do not account for the potentially diverse feasibility challenges (e.g., technological or behavioral) across different types of interventions. Overall, in the reviewed literature, supply-side interventions tend to be modeled more structurally and with greater detail on how each intervention would be introduced and percolate through the system. Instead, most demand-side interventions assume the outcome of policies and therefore tend to be more stylized compared to supply-side interventions. As a result, the feasibility of different levels of ambition is not comparable across interventions (e.g., very-high ambition for diets vis-à-vis N&P management). The costing of alternative interventions and their applicability across different geographic regions and socioeconomic contexts is an important topic of further investigation.[16,120] Further research could extend our work to calculate effect sizes of a more diverse range of available on- and off-farm mitigation actions that relate to each of the interventions modeled here.

The four environmental limits and the eight environmental indicators selected to represent them were chosen due to their abundance and consistent use in the food system modeling literature, ensuring adequate sample sizes for statistical analysis. This meant that some indicators that are better proxies of risk for specific environmental limits, such as nutrient-surplus indicators,[5,100] could not be used in our analysis. Similarly, the food system is a major driver of impact across several other environmental limits that were not considered here (Note S6), most notably exerting a significant impact on biosphere integrity.[15] While our estimates of environmental limits encompassed the wide uncertainty ranges incorporated in published estimates and a range in potential future shares of the global food system (Note S2), studies highlight the added importance of spatially explicit assessments that account for both local and global impacts.[5,9,100] Beyond environmental limits, a sustainable food system must also adhere to health and Earth system justice principles.[5,31] While our diet combinations are compliant with caloric food security requirements (Note S4), the aggregated diet predictors used in our synthesis inherited the diversity in plant calories assumed in the underlying studies. Our diet combinations thus cannot guarantee micronutrient adequacy without fortification or supplementation, especially in the case of the low-ASF diet, which may be subject to similar micronutrient shortfalls to the EAT-Lancet diet.[137] Our analysis could be extended to cover broader aspects of health and Earth system justice.

The global scope and statistical nature of our analysis presents limitations. First, we introduced bias by aggregating all training data to the global level. Despite using strict study inclusion criteria to ensure a comparable coverage of food commodities (Note S3), the assumed response of the statistical models to different scenarios represents the pooled response of the underlying models at the global level. While we used a large sample of model runs to ensure good coverage of the scenario space, our results do not fully reflect any non-linear regional responses to a given scenario that could add up to significant changes in the global model response (see Note S6 for a more detailed overview of modeling assumptions and limitations). Second, the statistical models did not allow us to encompass all possible interventions and their interactions. Although they were formulated with a process-based logic following that of the underlying models, which enables interactions between interventions (e.g., changes in diets occurring concurrently with changes in feed efficiency or feed composition), they do not encompass all processes modeled in the original models and are therefore not intended to fully emulate their individual responses (Note S5). For example, we did not consider parameters such as pasture productivity,[138] distinction between rainfed and irrigated yields, explicit modeling of land-use regulation and conservation actions,[20] or the potential for non-linear responses to efficiency parameters such as WUE or NUE or declining spatial efficiency across regions[139,140] (Note S6). Finally, we did not account for interactions between intervention levels and environmental limits. Such interactions could have an effect on risk calculations (for example, where rapid dietary transitions alter the remaining carbon budget due to their significant methane abatement).[25]

RESOURCE AVAILABILITY

Lead contact

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Materials availability

This study generated no new materials.

Data and code availability

Code to replicate the analysis is freely available and can be accessed through the following open access GitHub repository: https://github.com/MichalisHadjikakou/GFSI-MRM. The version of the model used to produce all results presented in the manuscript is stored in the following Zenodo release: https://doi.org/10.5281/zenodo.14523155. All supplemental data and extended results are available at https://doi.org/10.5281/zenodo.15515521.

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AUTHOR CONTRIBUTIONS

Conceptualization, M. Hadjikakou and B.A.B.; methodology, M. Hadjikakou and B.A.B.; software, M. Hadjikakou and E.A.M.; validation, M. Hadjikakou and B.A.B; formal analysis, M. Hadjikakou; data curation, M. Hadjikakou, N. B., O.G., J.G.C., J.M.M., B.L.B., A.M., I.W., M.A.S., K.D., K.F.D., S.P., M.S., M.C., G.S.M., E.R., B.B., N.T.G., D.W., J.C.D., A.D., M.C.T., P.P., M.S., C.L., J.C., V.H., E.E., L.P., N.P.S., A.F.B., T.G.M., and H.V.; writing – original draft, M. Hadjikakou; writing – review & editing, M. Hadjikakou, N.B., O.G., J.G.C., J.M.M., B.L.B., A.M., I.W., M.A.S., K.D., K.F.D., S.P., M.S., M.C., G.S.M., E. R., B.B., N.T.G., D.W., J.C.D., A.D., M.C.T., P.P., M.S., C.L., J.C., V.H., E.E., L.P., N.P.S., A.F.B., T.G.M., H.V., D.M.-D., K.-H.E., M.A.P., M. Herrero, P.D., X.Z., and B.A.B.; visualization, M. Hadjikakou; project administration, M. Hadjikakou; funding acquisition, M. Hadjikakou and B.A.B.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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