Bundling measures for food systems transformation: a global, multimodel assessment

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Summary

Background Current food systems leave one in ten individuals at risk of hunger while driving unsustainable environmental impacts. Inaction risks further exacerbating negative impacts on both human and planetary health. These challenges emerge from complex system interactions, requiring approaches that engage with this complexity and consider how transformation measures interact across food systems. We aimed to quantify the magnitude and uncertainty of the impacts of key food systems transformation measures both individually and in a bundle using an ensemble of global economic models.

Methods In this global multimodel assessment, we applied an ensemble of ten state-of-the-art global economic models to evaluate the potential of four key measures in transforming food systems: increasing agricultural productivity, halving food loss and waste, shifting towards healthier diets, and economy-wide climate mitigation policies aligned with limiting warming to 1·5°C. The scenarios used a middle-of-the-road shared socioeconomic pathway for population and gross domestic product growth, climate impact data from Jägermeyr and colleagues, Thornton and colleagues, and Nelson and colleagues, and dietary targets based on the EAT–*Lancet* healthy reference diet, with model simulations conducted from 2020 to 2050. We then assessed the effect of these measures in isolation and in combination in a bundled scenario. To further understand the interactions between these measures, we conducted a decomposition analysis that distinguishes between the individual effects of a measure (effect when implemented alone), total effects (its contribution within the bundle), and interaction effects (the difference between total and individual effects). This approach aimed to show complementarities and trade-offs that emerge when multiple measures are implemented simultaneously.

Findings Our analysis showed that individual measures in isolation are insufficient to achieve high-level environmental objectives and might generate unintended consequences. In contrast, bundling measures produces co-benefits: avoiding 50% of projected agricultural greenhouse gas emissions by 2050 and almost 20% of anticipated land conversion, while moderating food price increases associated with ambitious climate change mitigation policies. Our decomposition analysis further shows that measures can have varying effects across different dimensions. Although dietary shifts and climate mitigation policies are the largest drivers of environmental benefits (each contributing to a median decline of >10 percentage points in non-CO_2 emissions and 5 percentage points in agricultural land use globally), productivity improvements and reducing food loss and waste play essential roles in moderating price increases (each contributing to a median decline of >5 percentage points in average prices).

Interpretation This study highlights the importance of implementing coordinated approaches to food system transformation and climate change mitigation rather than relying on isolated interventions. Comprehensive transformation requires understanding how supply-side and demand-side changes can interact with climate mitigation policies, enabling policy makers to design intervention packages that maximise benefits while minimising trade-offs across environmental, economic, and social dimensions.

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Introduction

Although increased food production has helped feed a growing global population, it has simultaneously contributed to unsustainable agricultural land expansion,[1] water use,[2,3] accelerated biodiversity loss,[4] and the climate crisis.[5–7] Embedded food system inequalities mean that one in ten individuals remains at risk of hunger, while more than 2 billion people have overweight or obesity.[8] Approximately one-third of all food produced globally is either lost during production and distribution or wasted at retail and consumer levels, representing both a loss of valuable nutrition and substantial environmental impacts.[9] Failure to address these problems and transform our current food systems risks perpetuating and exacerbating food insecurity, malnutrition in all its forms, and environmental degradation,[10] precluding the achievement of multiple Sustainable Development Goals.[11–13]

Shifting to healthy diets,[14,15] reducing food loss and waste,[9] and improving production practices[16] can each reduce the environmental impacts of our food systems.[13,17]

Research in context

Evidence before this study

The first EAT–*Lancet* Commission published in 2019 highlighted the crucial intersection of human and planetary health. This Commission, along with other seminal research, has established that food systems both substantially contribute to and are profoundly affected by environmental degradation and climate change. This bidirectional relationship increasingly challenges our ability to provide healthy diets that remain accessible and affordable to all. A systematic review published in 2023 covering 2 years post-publication of the first EAT–*Lancet* Commission showed its substantial influence on food systems discourse. Although sentiment about the report has been largely positive, the review noted limitations, including insufficient attention to socioeconomic dimensions and the feasibility of implementing an EAT–*Lancet* food systems transformation. We searched Scopus, Web of Science, and PubMed for English-language publications from database inception to Sept 11, 2025, using the keywords ("food system*" OR "agri* system*") AND (transform* OR sustainab*) AND (model* OR scenario*) AND ("climate mitigation" OR "diet* shift*" OR "food waste" OR "food loss" OR productivit*) AND ("economic model*" OR "general equilibrium" OR "partial equilibrium" OR "rebound effect*" OR "economic feedback*"). This search yielded 41 articles after removing duplicates, with 26 published after the first EAT–*Lancet* report (2020 or later). 16 of these studies had a global spatial scope. Four of these global studies examined how reducing food loss and waste could improve both health and environmental indicators, two focused on the co-benefits of dietary shifts for health and climate change mitigation, and one explored the impacts of climate mitigation on future food prices. Recent global reports, such as the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Food System Economics Commission, and the Intergovernmental Panel on Climate Change, have highlighted the need for nexus approaches that combine both demand-side and supply-side measures in achieving multiple objectives such as food systems transformation and climate mitigation. When we added keywords related to interactions and bundled actions to our search (AND ("trade-off*" OR "tradeoff*" OR "co-benefit*" OR "cobenefit*" OR "complementarit*" OR "synerg*" OR "nexus approach" OR "interaction*" OR "multiple objective*" OR "bundled action*" OR "bundling action*" OR "bundled measure*" OR "decomp*")), the list narrowed to nine publications. None of these previously published works have assessed the socioeconomic and environmental impacts and trade-offs of shifting to healthier diets, reducing food loss and waste, improving productivity, and climate change mitigation on food systems both individually and in a bundle, using a multimodel ensemble of dynamic global economic models.

Added value of this study

This study advances our understanding of food system transformations in three ways. First, it leverages an ensemble of ten state-of-the-art global economic models to capture a broad range of possible outcomes and dynamic economic feedback. Second, it systematically assesses the potential contributions of four key transformation measures (increasing agricultural productivity, reducing food loss and waste, shifting to healthier diets, and mitigation and land-use policies) both individually and in combination. Third, the study includes a decomposition analysis that distinguishes between the effects of the four transformation measures implemented in isolation versus their effects in the bundled scenario, showing interactions that can lead to complementarities and trade-offs when bundling food systems transformation measures.

Implications of all the available evidence

The findings suggest that siloed approaches to food system transformation are inadequate to address interlinked environmental, health, and economic objectives. Although each measure shows benefits on its own, they all face limitations and trade-offs when implemented in isolation. A comprehensive transformation that bundles interventions across supply and demand sides, in conjunction with climate mitigation and land-use policies, achieves substantially greater environmental benefits while dampening potential trade-offs in food affordability seen in land-based climate change mitigation. Understanding complex interactions of the bundled measures is essential for prioritisation, risk assessment, resource allocation, and effective decision making. Moreover, the high model uncertainty of food prices in scenarios that include diet shifts highlights the need for future research to develop more coherent narratives of dietary change and sustainable development, and for monitoring important food system indicators to prepare for both price increases and decreases.

However, a nexus approach that acknowledges the complex interactions within food systems and their connections to climate, health, and environmental systems is needed.[18] Addressing emergent properties of these complex interactions, such as food insecurity and environmental degradation, requires bundling transformation measures and integrating them with broader multisectoral efforts such as climate change mitigation.[18–21] As part of the second EAT–*Lancet* commission,[22] which explores the potential of a food system transformation that can provide healthy diets for all from sustainable and just food systems, we build on previous work and explore the complexity of the potential consequences of such a food system transformation in three ways.

First, we applied an ensemble of ten state-of-the-art global economic models that include both general (whole-of-economy) and partial (detailed sector) equilibrium models, with varying geographical, sectoral, and temporal resolutions (appendix pp 2–7). The diverse structures of the ensemble facilitate a broader exploration of potential consequences of a food system transformation than single models, capturing an important range of possible outcomes, dynamic economic feedback, and market effects. The ensemble can also help to highlight where there is greater confidence in understanding system dynamics (ie, where the models agree), and to point to areas in need of more research and modelling (ie, where the models show a wider range of outcomes).

Second, we assessed the potential contributions of four key transformation measures on food prices and environmental impacts both in isolation and in combination. We evaluated a business-as-usual (BAU) baseline scenario, which represents a continuation of current trends and does not consider more ambitious climate action beyond currently implemented national policies. Against this baseline, we evaluated three transformation measures suggested in the EAT–*Lancet* Commission reports and other seminal work as key drivers for achieving healthier and more sustainable food systems:[13,22,23] increasing productivity (PROD), reducing food loss and waste (WAST), and shifting to healthy diets (DIET). We also assessed how food systems transformation could contribute to broader climate change mitigation by evaluating both a standalone climate change mitigation policy scenario (MITI) and a bundled scenario that combines an EAT–*Lancet* style food system transformation with ambitious climate goals (EAT–*Lancet* food system transformation with mitigation [ELM]).

Last, bundled measures aimed at transforming complex systems can often produce non-additive or non-linear interactions.[24] These interactions can manifest as either complementarities, where combined measures yield benefits greater than their individual effect, or trade-offs, where one measure might dampen the effectiveness of another. Therefore, getting a better understanding of the consequences of these measures both individually and in combination is crucial for prioritisation, risk assessment, resource allocation, and effective decision making. We used a decomposition analysis[16,24–27] that distinguishes between individual effects (the effect of a single measure implemented alone), total effects (the contribution of a measure within the comprehensive scenario), and interaction effects (the difference between total and individual effects, showing complementarities and trade-offs).

Methods

Ensemble of global economic models and model intercomparison

In this global multimodel assessment, we facilitate a broader exploration of potential economic and environmental consequences of a food system transformation by applying an ensemble of global economic models, recognising that each model represents food system dynamics in a somewhat different way (ie, model structure and spatial and temporal resolutions). This ensemble was composed of ten models, which included a mix of computable general equilibrium and partial equilibrium models: AIM, CAPRI, ENVSIAGE, FARM, GCAM, GLOBIOM, IMAGE, IMPACT, MAGNET, and MAgPIE (see appendix p 2 for links to model documentation and appendix pp 2–7 for a full description of participating models). Dynamic economic models are essential tools for understanding the complex trade-offs, feedback effects, and potential impacts of food systems transformation, including effects on prices, resource use, and environmental outcomes that can arise from interconnected markets. The models that were included in this exercise have participated previously in model intercomparisons as part of the Agricultural Model Intercomparison Project, and in high-impact global assessments.[11,16,28–31] The model intercomparison process took place from March 14, 2023, to Aug 19, 2025, involving multiple iterations of scenario submissions to validate and harmonise scenario implementation across the model ensemble.

See Online for appendix

Scenario specification and experiment design

To provide a consistent analytical framework, this multimodel assessment of food system transformation is embedded within carefully constructed scenarios. The scenario components and an overview of model implementations are shown in the table (full scenario specification is in appendix p 8). Detailed model-specific implementations are provided in the appendix (pp 16–26). The scenarios modelled follow a middle-of-the-road shared socioeconomic pathway (SSP2[33]), which projects a global population of 9·6 billion (a 23% increase from 2020) and 127% growth in global gross domestic product (GDP) by 2050 compared with 2020 (appendix pp 10–11).

Input data underlying the three key food systems transformation measures were shared with the participating models. All scenarios were implemented using the latest SSP2 data[33,34] for population and GDP projections. Data on crop and livestock climate shocks were from Jägermeyr and colleagues[35] and Thornton and colleagues,[36] respectively.

	Description
Business as usual (BAU)	BAU scenario based on the middle-of-the-road shared socioeconomic pathway, following recent economic, technological, and dietary trends. There are no additional climate mitigation and land-use policies other than national policies that are already implemented.
Increased productivity (PROD)	Agricultural productivity increases consistent with the shared socioeconomic pathway of taking the greener road (SSP1), which represents a more sustainable and optimistic world with greater investments in agricultural research and technology compared with the BAU scenario. Models applied exogenous improvements to crop yields and livestock feed conversion efficiency following SSP1 assumptions. Several models also incorporated endogenous mechanisms where productivity improvements respond to economic incentives such as reduced interest rates, particularly in low and middle income regions (see appendix pp 16–18 for additional details on model-specific implementation of PROD).
Reduced food loss and waste (WAST)	Reducing food loss and waste consistent with Sustainable Development Goal 12.3 on halving per-capita food waste and reducing losses along the supply chain. Models applied exogenous reductions to loss and waste shares across different stages of the food supply chain (production, processing, retail, and consumption) and food groups, targeting a 50% reduction in these shares by 2050 (see appendix pp 18–20 for additional details on model-specific implementation of WAST).
Diet shift (DIET)	Shifting diets towards healthier consumption patterns consistent with the EAT–*Lancet* healthy reference diet.[22,32] Models implemented dietary shifts towards the EAT–*Lancet* healthy reference diet, primarily through exogenous shocks to shift demand curves or adjusting elasticity parameters that modify consumption patterns to align with recommended intake levels by food group and region by 2050. The models allowed for endogenous price and market responses to these demand shifts, with some incorporating region-specific adjustments to account for local food preferences and economic constraints (see appendix pp 20–23 for additional details on model-specific implementation of DIET).
Mitigation policies (MITI)	Climate mitigation and land-use policies aligned with achieving a 1·5°C target by 2100. Models achieved this through carbon pricing mechanisms that put a cost on greenhouse gas emissions, with carbon prices increasing over time. This incentivised shifts towards less emission-intensive production methods, adoption of mitigation technologies, limited land expansion, incentivised land-based carbon sequestration such as reforestation and afforestation, and increased demand for bioenergy crops. Several models also incorporated land-use policies such as forest protection (see appendix pp 23–26 for additional details on model-specific implementation of MITI).
Combined scenario (EAT–*Lancet* food system transformation with mitigation; ELM)	A scenario that combines PROD, WAST, DIET, and MITI (EAT–*Lancet* food system transformation with mitigation, or ELM).

BAU=business as usual. DIET=dietary shift. ELM=EAT–*Lancet* food system transformation with mitigation. MITI=mitigation policies. PROD=increased productivity. WAST=reduced food loss and waste.

***Table:* Scenario assumptions and overview of model implementation**

Climate impacts on four main crops (maize, wheat, rice, and soybeans) were mapped to the IMPACT model's 36 crop commodities according to their biophysical properties. Likewise, the livestock climate shocks for meat and dairy were mapped to beef, lamb, pork, poultry, and eggs, and to milk, respectively. The climate shocks that reflect the biophysical effects of changes in temperature and precipitation, without changes in management, were then combined with projections of agricultural productivity growth, which represent a general technology trend, from IMPACT. Mapping of climate impacts on crops and livestock to IMPACT commodities and additional details on data processing of exogenous yield assumptions are shown in appendix p 13. Agricultural labour productivity trends were based on data from Nelson and colleagues[37] and reflect global reductions in manual agricultural work capacity due to climate change (appendix p 14). The diet implementation required data on food consumption categorised by food group and region for both the benchmark and flexitarian diet; these data were provided by Springmann and colleagues[32] and the EAT–*Lancet* Commission[22] (appendix p 14).

Although we harmonised scenario narratives and input data as best as possible across the ensemble, the participating models differ in their structure, calibration datasets, and native approaches to implementing scenarios. These differences can result in varying baseline projections even when using the same underlying scenario assumptions and input data. Given that our focus was on evaluating scenario impacts rather than absolute values, we standardised results by examining relative changes from a common reference point. Therefore, to compare results across models, we calculated the percentage change to the value from a reference period (the year 2020) for each model independently. If a model did not provide a value for the reference period, we linearly interpolated the value using the nearest years before and after the reference period. This ensured that our analysis captured the directional impacts and relative magnitudes of transformation measures while accounting for the inherent diversity in model structures and calibrations within our ensemble.

Unless otherwise stated, we report the median result of the ensemble and the range. Where the range spans both positive and negative change, we include the number of models reporting in the same direction as the ensemble median.

Decomposition analysis

To quantify how different components of the ELM scenario contribute to environmental, economic, and justice outcomes, we conducted a decomposition analysis. Using an approach[24] that has been used in determining the contributions of scenario components to non-CO_2 emissions,[25] land-use change,[16] food security,[26] and planetary boundaries,[27] we assessed both the individual effects of each component of the ELM bundle and their interactions with other components (table 1).

The first set of scenarios isolated individual components by adding each one separately to the BAU scenario (eg, BAU_DIET adds only dietary changes to BAU; appendix p 8). The difference between these scenarios and BAU represents the individual effect of each component. The second set of scenarios removed components one at a time from the full ELM scenario (eg, ELM_DIET removed dietary changes from ELM; appendix p 8). The difference between ELM and these leave-one-out scenarios quantifies the total effect of that measure within ELM in percentage points, which includes both its direct effect (individual effect) and all its interactions with other components of ELM (see appendix pp 26–27 for more details).

The interaction effect for each component was calculated as the difference between its total effect and its individual effect. A small interaction effect indicates that the impact of the component is largely independent and additive. Conversely, a large interaction effect suggests the impact of the component is substantially modified by the presence of other components. When an interaction effect has the same sign as the total effect, it indicates complementary interactions with other components; an opposite sign indicates antagonistic relationships.

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

Driven both by population and economic growth, the BAU scenario projected a multimodel median increase in agricultural production of 38% (range 13–41) by 2050 compared with 2020 (figure 1 and appendix p 35 for ensemble coverage, median absolute deviation, and level of agreement). Resource-intensive commodities such as red meat[38] were projected to increase faster than cereals such as rice and wheat (appendix pp 29–31). This increased global production was associated with a median 10% (4–13) expansion in harvested crop area, a median increase in livestock animal numbers of 16% (11–22), a median increase in crop yields of 25% (17–36), and a median increase in livestock yields of 22% (19–25; figure 1 and appendix p 36).

Food affordability is essential for ensuring global food security and human wellbeing, as it directly affects nutritional access and quality of life. Despite a median increase in prices of 4% (range –28 to 34; six of eight models showed increase) over this 30-year period globally, all models suggested food would become more affordable on average as incomes were projected to increase by 85% in per-capita GDP over the same time period (appendix pp 10, 32), continuing historical food affordability trends over the past 50 years.[39]

Projected BAU increases in agricultural production would exacerbate existing environmental challenges (figure 2), with agricultural non-CO_2 (which includes methane and nitrous oxide greenhouse gases) emissions increasing by a median of 32% (range 7 to 50), equivalent to an increase from about 7·14 Gt CO_2 equivalent (CO_2e)[6] to 9·4 Gt CO_2e, and an expansion of agricultural land (which includes cropland and grassland) of 6% (1 to 7), increasing from 4800 Mha to almost 5100 Mha. This increase in agricultural land is likely to be at the expense of forests and natural vegetation, which were estimated to decline by 5% (1 to 6; appendix p 32). Increases in agricultural production also increased water use for crop irrigation (13% [–10 to 44]; six of seven models showed increase) and chemical input use (nitrogen use increasing by 41% [22 to 58] and phosphorous use increasing by 41% [36 to 46]). All of these suggest increasing risks of transgressing planetary boundaries, which could threaten the sustainability of projected gains in agricultural productivity and food affordability.

Assessing the individual effects of each transformation measure in isolation showed its benefits and strengths, but also its limitations and potential rebound effects. In the scenario with increased agricultural productivity (PROD) there was an estimated median increase in crop yields of 3% (range 3 to 8), with a modest effect on harvested crop area (median –2% [–7 to 5]; five of seven models showed decrease) by 2050 compared with BAU (figure 1). These modest reductions in harvested area were due to rebound effects, with increased productivity contributing to a median –5% (–17 to 1; seven of eight models showed decrease) change in agricultural prices, triggering an increase in food demand (1% [0 to 4]) and in production (1% [–1 to 8]; eight of nine models showed increase). Modest improvement along other environmental dimensions (ie, reducing emissions, land use, and water use) were also observed (figure 2).

Reducing food loss and waste (WAST) is projected to narrow the gap between food purchased and food consumed (appendix p 33), leading to a median –9% (range –13 to 1; seven of nine models showed decrease) change in food demand (figure 1), even as food intake stays above or near BAU levels (1% [–6 to 9]; seven of eight models showed increase). The reduction in food demand was estimated to lead to a median –5% (–14 to –2) change in producer prices and –7% (–10 to –1) change in production compared with BAU levels. Model results showed greater environmental benefits under WAST compared with PROD across emissions, land use, water use, nitrogen use, and phosphorus use (figure 2).

Shifting consumer behaviour towards healthy diets (DIET) was projected to reduce global agricultural production (median change –13% [range –27 to –2]), while fundamentally changing consumption patterns (figure 1). The substantial decrease in livestock demand (–35% [–54 to –29]) drives down

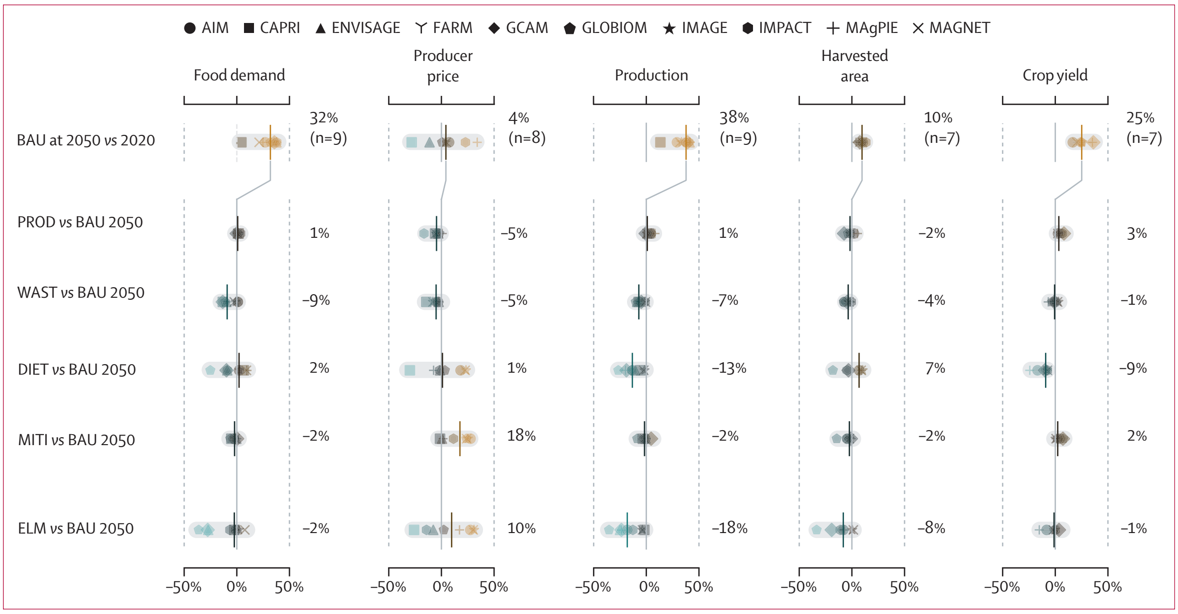

Figure 1: **Food system impacts across scenarios by 2050**
Percentage changes in food system indicators—food demand for agricultural commodities, agriculture producer prices, agriculture production, harvested area for crops, and crop yields—from 2020 to 2050 under a BAU scenario, and for counterfactual scenarios relative to BAU 2050, with a grey reference line connecting the BAU median (0% change point) across all panels. The dark vertical lines show the multimodel median, with median values shown to the right alongside the number of reporting models in parentheses. Coloured markers indicate individual model results, with colour intensity reflecting magnitude of change (darker shades closer to 0%, increasing saturation for larger changes, with orange indicating increases and blue indicating decreases from the reference point). The shaded region shows the full ensemble range. BAU=business as usual. DIET=dietary shift. ELM=EAT–*Lancet* food system transformation with mitigation. MITI=mitigation policies. PROD=increased productivity. WAST=reduced food loss and waste.

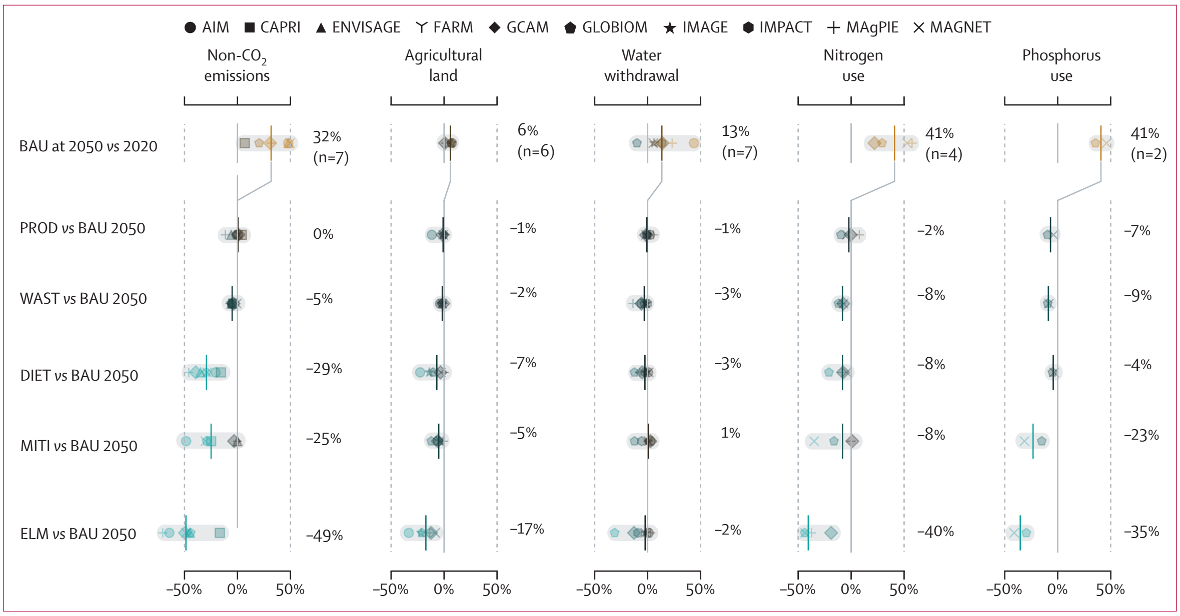

Figure 2: **Environmental impacts across scenarios by 2050**
Percentage changes in environmental indicators—non-CO_2 emissions from agriculture, agricultural land, water withdrawals for crops, nitrogen use for crops, and phosphorus use for crops—from 2020 to 2050 under a BAU scenario, and for counterfactual scenarios relative to BAU 2050, with a grey reference line connecting the BAU median (0% change point) across all panels. The dark vertical lines show the multimodel median, with median values shown to the right alongside the number of reporting models in parentheses. Coloured markers indicate individual model results, with colour intensity reflecting magnitude of change (darker shades closer to 0%, increasing saturation for larger changes, with orange indicating increases and blue indicating decreases from BAU). The shaded region shows the full ensemble range. BAU=business as usual. DIET=dietary shift. ELM=EAT–*Lancet* food system transformation with mitigation. MITI=mitigation policies. PROD=increased productivity. WAST=reduced food loss and waste.

livestock production (–34% [–52 to –23]; appendix p 28) and animal numbers (–33% [–36 to –30]; appendix p 36), which reduces agricultural methane emissions substantially (–37% [–51 to –17]; appendix p 31). Overall, these changes were estimated to lead to a decline in agricultural non-CO_2 emissions (–29% [–46 to –16]; figure 2). Although cropland could expand by 7% (–13 to 23; five of eight models showed increase; appendix p 32) due to increased demand for plant-based foods, in particular vegetables, fruits, and nuts (26% [–38 to 91]; seven of eight models showed increase; appendix p 29), grassland was estimated to decrease (–9% [–47 to –1]; appendix p 31), yielding an overall change in agricultural land of –7% (–23 to 1; seven of eight models showed decrease; figure 2).

There was low agreement across the models on the effect of DIET on average agricultural producer prices (median 1% [–30 to 23] increase; four of eight models showed increase; figure 1 and appendix p 35). This finding might be partially explained because a shift to a healthy diet simultaneously reduces demand for animal-sourced food, particularly red meat (predominantly ruminant meat; appendix p 30), while increasing the demand for vegetables, fruits, and nuts (appendix p 29). Notably, although the ensemble showed high agreement that the DIET scenario increases prices for vegetables, fruits, and nuts and decreases ruminant meat prices, there was uncertainty in the magnitude of the price increase of vegetables, fruits, and nuts (appendix p 35), contributing to the uncertainty in average agricultural prices.

Climate mitigation policies on their own (MITI) were estimated to avoid 25% (range 0 to 48) of the projected agricultural non-CO_2 emissions and 5% (1 to 12) of projected land expansion compared with BAU (figure 2). However, MITI might increase demand for water for irrigation (1% [–12 to 3]; five of seven models showed increase) due to increased demand for crops for bioenergy and due to restrictions on land expansion contributing to increased intensification on existing agricultural land, as reflected in an increase in crop yields by 2% (0 to 8; figures 1, 2). The MITI scenario increases production costs through emission pricing on inputs (eg, fertiliser costs) and outputs (eg, methane emissions), disproportionately affecting ruminant production (appendix p 30). Moreover, limiting land expansion and incentivising the production of bioenergy crops can create trade-offs with food production and can lead to higher agricultural prices.[26,40,41] The multimodel ensemble projected a median producer price increase of 18% (–1 to 28; seven of eight models showed increase), with mitigation policies reducing future GDP growth (–2% [–1 to –5]), noting that possible benefits of climate action for GDP were not modelled in this study (eg, improved labour productivity from avoided climate change). In combination, MITI contributes to less affordable food compared with BAU by 2050 (appendix p 32), even though food would still be more affordable compared with 2020 levels, on average (appendix p 32).

When bundling PROD, WAST, DIET, and MITI together in a combined scenario (ELM), we observed better environmental outcomes than for any individual scenario. In ELM, agricultural non-CO_2 emissions were estimated to decline by 49% (range 17 to 71), agricultural land use by 17% (8 to 33), water use by 2% (–31 to 3 change; five of seven models showed decrease), nitrogen use by 40% (19 to 47), and phosphorus use by 35% (30 to 41), all compared with BAU (figure 2). For four of the seven models, this is equivalent to reducing non-CO_2 emissions below 5 Gt CO_2e, and for all six reporting models, this is equivalent to agricultural land use going below 2020 levels. Although by 2050 producer prices increase in the ELM scenario (by 10% [–26 to 31] compared with BAU; five of eight models showed increase), this increase is less than under the MITI scenario alone (figure 1).

Under ELM, we observed substantial reductions in non-CO_2 emissions, with the decomposition analysis showing that DIET is the biggest driver of reducing global agricultural non-CO_2 emissions, contributing a decrease of 17 percentage points (range 3 to 44; figure 3A). The MITI scenario complements this effect, as climate mitigation and land-use policies contribute a reduction of 11 percentage points (0 to 40; appendix p 34). PROD and WAST contribute modestly to emissions reduction when bundled in ELM (–1 percentage point [–16 to 0] and –3 percentage points [–29 to –1], respectively). The primary drivers of reduced agricultural emissions in both DIET and MITI were reductions in ruminant animal numbers and, as such, the effect of combining DIET and MITI in ELM was less than the sum of the individual effects. Nevertheless, their interaction effects show that although there is some redundancy across these two measures, there are also complementarities as less dietary change or ambitious mitigation is needed to achieve the same reduction in animal numbers as for each intervention in isolation (interaction effect on emissions for DIET and MITI when bundled *vs* in isolation show median increase of 11 percentage points [–5 to 20] for DIET; six of seven models showed increase, and 8 percentage points [–18 to 19] for MITI; five of seven models showed increase). Bundling measures in ELM achieved greater emission reductions at a given carbon price than implementing mitigation policies alone.

There were similar findings for agricultural land, with larger reductions in agricultural land in ELM than for any measure alone, with the largest drivers being MITI and DIET, with each contributing 5 percentage points (range 2–13) and 5 percentage points (2–15) decrease in agricultural land, respectively. PROD and WAST contributed less to reduced agricultural land than DIET or MITI, accounting for a reduction of 2 percentage points (0–5) and 1 percentage point (1–2), respectively (figure 3B).

All four scenarios contribute to reductions in emissions and land use; however, the measures can act in opposing directions to each other in the case of water use. Although there was an overall reduction in water use under ELM, MITI could increase water use (1 percentage point [range –13 to 17]; five of seven models showed increase), whereas DIET

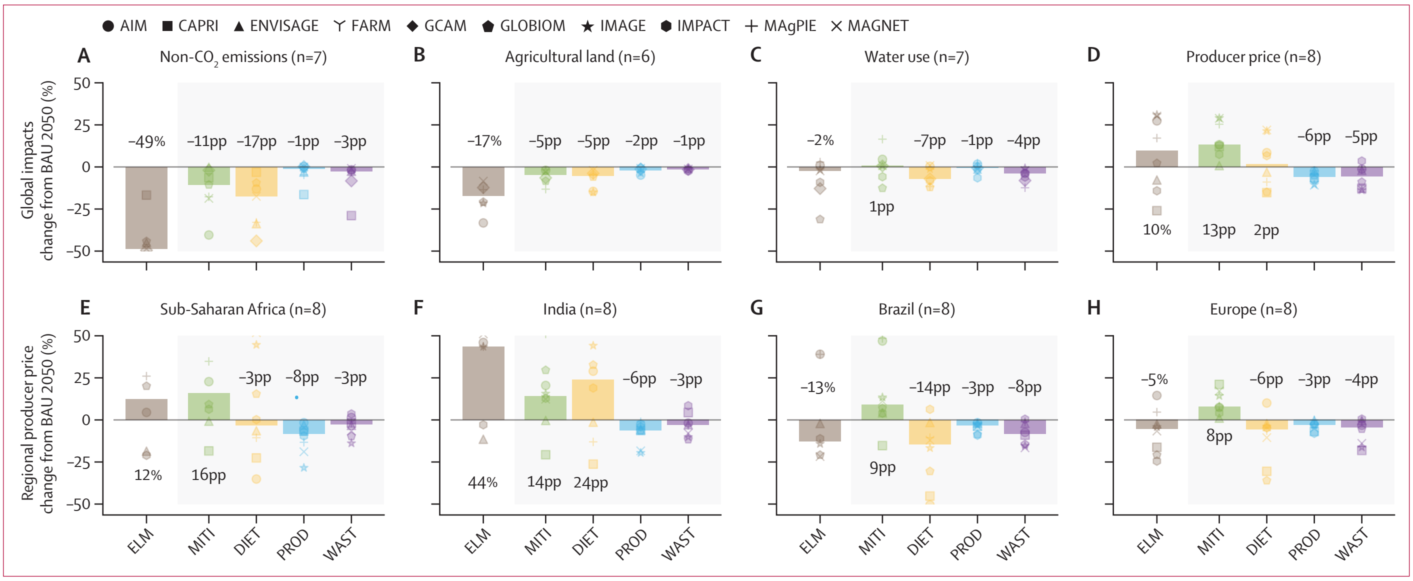

Figure 3: **The decomposed impacts of key food systems transformation measures within ELM compared with BAU 2050**
The decomposed impacts of key food systems transformation measures within ELM compared with BAU 2050. Median cumulative global impact of ELM (as percentage change from BAU 2050) and median total effects of MITI, DIET, PROD, and WAST within ELM (as pp changes from BAU 2050) for (A) non-CO_2 emissions, (B) agricultural land, (C) water use for crops, and (D) agriculture producer prices. Individual model results are indicated by model-specific markers. The impacts of these measures on average agriculture producer prices are shown in four regions: (E) sub-Saharan Africa, (F) India, (G) Brazil, and (H) Europe. BAU=business as usual. DIET=dietary shift. ELM=EAT–*Lancet* food system transformation with mitigation. MITI=mitigation policies. pp=percentage points. PROD=increased productivity. WAST=reduced food loss and waste.

contributed –7 percentage points (–12 to 1; five of seven models showed decrease), WAST contributed –4 percentage points (–15 to –1), and PROD contributed –1 percentage point (–7 to 2; five of seven models showed decrease) to changes in water use (figure 3C). The decomposition analysis highlights the importance of combining measures that increase the efficiency of food systems (PROD and WAST) and promote more responsible consumption (DIET and WAST) to achieving more sustainable agricultural water use.

Across most environmental outcomes, DIET and MITI were the largest drivers, with PROD and WAST contributing more modestly to reducing the environmental impact of food systems. However, focusing solely on dietary shifts or ambitious climate mitigation policies without complementary measures that increase the efficiency of food systems (PROD and WAST) risks increasing problems of food affordability, which could challenge the adoption of healthy diets by consumers on lower incomes, perpetuating existing food system inequalities.

As previously described, MITI leads to higher producer prices compared with BAU, contributing 13 percentage points (range 1 to 29) within ELM (figure 3D). Globally, the effect of DIET on average agricultural producer prices in ELM shows low agreement across the ensemble, where four of the eight models project an increase in producer prices (2 percentage points [–18 to 15]). Low agreement across the ensemble is explained not only by offsetting demand shifts between food groups (decreasing ruminant demand and increasing demand for vegetables, fruits, and nuts) in a transition to a healthy diet, but also by complex interactions with the other measures. For example, DIET's reduction in ruminant demand exerts downward pressure on ruminant prices, whereas MITI increases ruminant producer prices through emissions pricing (appendix p 34). Similarly, although improvements in managing food loss and waste in WAST reduce production costs for perishable foods such as fruits and vegetables, DIET's increased demand for these commodities can drive their prices upward (appendix p 34).

Regional results highlight greater model agreement in high-income and middle-income regions where diets are characterised by higher consumption levels of red meat (eg, Brazil and Europe) than in low-income and middle-income income regions. In sub-Saharan Africa, models show low agreement on whether DIET increases or decreases the overall cost of producing a healthy diet, reflecting complex trade-offs between reduced livestock value and volume of production and increased demand for vegetables, fruits, and nuts (figure 3E). This uncertainty highlights potential food affordability challenges in sub-Saharan Africa, owing to relatively high levels of food insecurity across the region, as well as the importance of agriculture and, in particular, the livestock sector for livelihoods in the region.[42] Two of the three models (AIM and ENVISAGE) that report food expenditure show increasing average regional food affordability by 2050 compared with 2020; however, one model (MAGNET) shows that in DIET, MITI, and ELM there remains a risk of food becoming less affordable if the transformation is not managed effectively (appendix p 33). In India models showed a median increase in producer prices under DIET due to relatively low meat consumption levels, such that shifts towards a healthy diet in India are characterised mostly by increased demand for vegetables, fruits, and nuts, which drives up their prices, and suggests that healthy diets could be more expensive than BAU diets by 2050 (figure 3F).

Conversely, in Brazil and Europe, where there is over-consumption of red meat, DIET drives a decline in producer prices due to decreased demand for ruminant products that leads to more affordable diets and an overall decline in aggregate agricultural prices (figure 3G, H).[43]

The PROD scenario enables more efficient resource use on existing agricultural land, helping to lower production costs and reduce environmental pressures through increased technical efficiency. Although PROD contributes modestly to environmental objectives, partly due to price–demand feedback effects, it plays a crucial role in moderating price increases, contributing a change of –6 percentage points (–11 to –2) in producer prices. Given that the affordability of healthy diets is a serious limiting factor to their adoption, these results suggest the importance of including investments in increased productivity in food system transformation. Indeed, in both sub-Saharan Africa and India, there is high agreement across the ensemble that PROD decreases producer prices (figure 3E, F), highlighting the ongoing importance of investing in research and development for sustainable agricultural production.[43,44]

Additionally, without targeted interventions for reducing food loss and waste, shifts in diets towards greater consumption of perishable foods could increase waste across the food system[45] and could challenge access to and consumption of fruits and vegetables to recommended levels.[43] This emphasises the importance of coupling DIET with targeted measures for reduction of food loss and waste to manage potential trade-offs effectively. It also highlights the need for further investigation of regional and sectoral effects of these transformation measures.

Discussion

Our findings suggest that although each scenario has benefits on its own, siloed approaches can have trade-offs that diminish their effectiveness and are often inadequate to address interlinked environmental, health, and economic objectives, confirming findings from previous studies, including the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services,[18] Food Systems Economics Commission,[46] and the Intergovernmental Panel on Climate Change.[11] The inherent complexity of food systems necessitates a nexus approach and bundling measures across supply and demand sides in conjunction with climate mitigation to achieve environmental benefits while dampening possible trade-offs in food affordability.

Our modelling highlights there is substantial uncertainty in the final effect of bundling multiple measures on average agricultural prices globally in ELM. This uncertainty operates at multiple levels and stems from several sources. First, there is high agreement across models in the direction of price changes for most individual measures: MITI increases prices, whereas PROD and WAST decrease prices through improved food system efficiency and lower production costs. However, although dietary shifts emerge as one of the largest drivers of reducing the environmental impacts of agriculture globally, DIET shows low model agreement, with models split on whether dietary shifts increase or decrease aggregate agricultural prices. At the sectoral level, although there is high agreement that DIET increases prices for vegetables, fruits, and nuts and decreases prices for ruminant meats, high uncertainty in the magnitude of price changes for vegetables, fruits, and nuts (likely due to aggregation across diverse agricultural commodities in this sector) contributes to uncertainty in average agricultural price directions. Second, when bundling measures in ELM, these opposing price effects create compounded uncertainty in overall price outcomes. The opposing effects of DIET and MITI on ruminant meat prices further amplify this uncertainty in both direction and magnitude across models. Third, this uncertainty also stems from scenario construction, where there were limited narrative elements explaining how dietary change and sector restructuring was to be achieved (ie, taxes, subsidies, or regulations), such that producers re-oriented production based solely on market prices.

Importantly, although there is high agreement across models on the biophysical effects of ELM (such as reductions in agricultural emissions and land use), prices are economic residuals that emerge from complex market interactions and thus exhibit greater uncertainty. This suggests that although achieving these changes in the food system is more likely to improve progress towards environmental goals, there is greater uncertainty about the socioeconomic and justice consequences of a food system transformation. This study begins to explore this space, but highlights the need for higher regional and sectoral resolution in assessing dietary shifts and mitigation policies, especially for sectors affected by such shifts (ie, the livestock sector[47]), more coherent narratives of dietary change and sustainable development,[48] and better monitoring of food system indicators to prepare for both price increases and decreases.[49] The study by Kuiper and colleagues[50] offers valuable insights into mechanisms of dietary change, showing that the method of achieving dietary shifts substantially influences costs with price incentives for healthy food production and consumption potentially proving more cost-effective than consumer behaviour interventions.

Understanding potential interactions between measures and the uncertainty of their effects is particularly important for policy makers and stakeholders seeking to achieve food system transformations. Food systems transformations present heterogeneous challenges and benefits across regions[51] and sectors,[47] which will require context-specific approaches. Our decomposition analysis offers a framework for assessing how specific interventions could contribute to local objectives and priorities. This is particularly crucial in areas where agriculture contributes to a substantial portion of the economy, as restructuring food systems could create affordability challenges through higher prices for healthy foods and disruptions to agricultural employment and wages.

For example, globally and across the regions, MITI increases producer prices in ELM by raising production costs. Meanwhile, the effect of DIET on average agricultural producer prices and the cost of producing a healthy diet depends on existing agricultural production patterns, current demand, and regional capacity for reallocating resources. In regions where food security is an urgent concern, such as sub-Saharan Africa and India, prioritising the efficiency of the food system through improved productivity and reduced food loss and waste can help moderate prices and improve access to nutritious foods. Indeed, historical investments in agricultural productivity have contributed substantially to food affordability.[39] On the other hand, in regions where a dietary transition towards healthier patterns could reduce food prices, such as in Brazil and Europe, prioritising shifts to healthier diets can help capture the benefits of reduced environmental pressures while maintaining economic stability for agricultural sectors. However, policy makers should carefully consider how to achieve these dietary shifts, as they can substantially affect producers of ruminant meat in these regions. These regional and sectoral variations highlight the need to understand the distributive impacts of food system transformation across different contexts. Factors such as sectoral specialisation, geographical location, demographics, and development trajectories all influence how different measures complement or potentially conflict with each other. This complexity demands careful analysis of region-specific and sector-specific challenges to design effective transformation strategies.[48,49,52,53]

This study has limitations that point towards valuable future research directions. Our analysis focuses on the potential outcomes when fully achieving the EAT–*Lancet* recommended diet,[22] but there are multiple pathways to healthier diets, including partial adoption scenarios (eg, prioritising dietary change in some regions first, or closing the gap to healthy diet by 2050), varying timelines of adoption, and sequencing of the various interventions, that would yield different trade-offs and implementation challenges. The model ensemble primarily employed carbon pricing as the main policy lever for implementing climate mitigation, yet this represents only one pathway to achieving 1·5°C targets. Alternative mitigation strategies such as financial subsidies to producers to adopt manure management technologies, technology standards, sustainable and ecological intensification, or land-use restrictions could produce substantially different outcomes for food systems. Additionally, the participating models share some fundamental economic assumptions that might introduce systematic biases in our projections. Future research would benefit from incorporating more diverse modelling approaches (eg, system dynamics and agent-based models) and a wider range of socioeconomic assumptions (eg, wider range of population and growth scenarios) and potential solutions, including novel technologies and practices such as circular food systems,[54] nature-positive solutions, and novel feeds and foods, that might play crucial roles in real-world food system transformation beyond what was considered in these stylised scenarios.

The findings from this multimodel study are clear: there is no single solution to the intertwined challenges of environmental sustainability and global food security. Instead, the path forwards demands a holistic transformation of our food systems—one that simultaneously advances sustainable production, promotes responsible consumption, and implements economy-wide climate mitigation. The challenges of food system transformation extend beyond technological feasibility to encompass complex social, behavioural, and political dimensions.[20,55] Although our analysis shows the technical and economic potential of these transformations, successful implementation will require coordinated action across diverse stakeholders, from farmers and food processors to consumers and policy makers. Future research could address essential questions about equity, regional implementation pathways, and effective policy mechanisms to support this transition, including understanding how different regions and sectors can navigate the transformation while ensuring food security and economic stability for their agricultural sectors.

Contributors

DM-D, MH, and MSu conceptualised the study. MSu performed the formal analysis, visualised the results, and wrote the original draft of the manuscript. TDO, MG, and MSu were responsible for the research coordination of the study. FB, LB, BLB, AB, MC, DM-CC, TdL, JD, SD, SFr, SFu, TH, PH, JH, MKo, MKu, PK, HL-C, HL, AM, IPD, APa, APo, RS, ES, TS, KTa, GT, FT, KTs, W-JvZ, HvM, DvdM, DVV, IW, KW, and XZ were responsible for implementing and running the study scenarios in their models. JJ, CM, GN, MSp, and PT provided input data to the scenarios. All authors have access to the data. MSu, TDO, MG, DM-D, and MH accessed and verified the data. All authors contributed to the editing and reviewing of the final manuscript, and the decision to submit for publication. MH acquired funding for the study. DM-D and MH provided overall supervision and study management.

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Data sharing

Model results data that support the findings of this study as well as the code to reproduce the figures and analyses are available at Zenodo.

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