A food system transformation can enhance global health, environmental conditions and social inclusion

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Abstract

The current global food system has detrimental outcomes for global health, environmental conditions and social inclusion. A coherent vision of a desirable food system can guide a sustainable food system transformation and help to structure political processes and private decisions by quantifying potential benefits, facilitating debates about co-benefits and trade-offs, and identifying key measures for desirable change. Such a transformation requires integrating measures targeting human diets, livelihoods, biosphere integrity, and agricultural management.
Here, we apply a global food and land system modeling framework to quantify the impacts of 23 food system measures by 2050. Our multi-criteria assessment shows that a food system transformation can improve outcomes for health, the environment, social inclusion, and the economy. All individual measures come with trade-offs, particularly those targeting agricultural management, while few trade-offs and multiple co-benefits are linked to dietary change measures. By combining measures in packages, trade-offs can be reduced and co-benefits enhanced. We show that a sustainable food system also requires a transformation of the overall economy to stop global warming, reduce absolute poverty, and create alternative employment options. Within the context of a cross-sectoral sustainable development pathway, the food system transformation improves 14 of our 15 outcome indicators.

Introduction

The global food system falls short of long-term targets for global health, environmental conditions, and social inclusion[1,2]. Malnutrition is the leading global health risk, causing 11 million deaths and the loss of 255 million disability-adjusted life years per year[3,4]. While the decline in undernutrition stagnates, overnutrition-related health risks are rapidly increasing[2]. The food system is the main driver of biodiversity loss, nitrogen pollution, and water withdrawals and contributes about one-third of global greenhouse gas (GHG) emissions [5,6]. Baseline scenarios produced by global food system models project a continuing decline in environmental conditions[7,8]. 1.3 billion people receive jobs and income from the food system, mostly in agriculture, yet often under precarious conditions[9,10]. At the same time, income inequality in combination with the regressive effects of food as a necessity-good makes food expenditures an important determinant of poverty. Food expenditures, in turn, are highly sensitive to shocks such as the income losses during the COVID-19-pandemic or food price spikes after Russia's invasion of Ukraine[10–12].

Concrete and plausible visions of a desirable future can guide transformative change by fostering a debate about a shared vision[13–15]. The 2022 UN Food System Summit highlighted the need for sustainable transformation pathways that cover food systems comprehensively[1,16]. Such pathways can serve as benchmarks for measuring progress, facilitate coordination, and allow for debating the effectiveness of measures and potential trade-offs with other desirable outcomes[13–15,17]. Comprehensive visioning scenarios are scarce in the literature[18], yet food system models that use integrated assessment methods can derive such pathways: they can simulate long-term and large scale transformations, ensure plausibility and internal consistency, and integrate the effects of measures across multiple parts of the food system[8,19,20].

Here we provide a Food System Transformation (FST) pathway,which we propose as one possible normative benchmark for a desirable future of the global food system. Our assessment starts with a reference baseline scenario ($\text{BASE}_{\text{SSP2}}$) following the middle-of-the-road Shared Socioeconomic Pathway SSP2[21]. We estimate 15 social-welfare related outcome indicators (Extended Data Table 2) which comprehensively span the four dimensions of health, environment, social inclusion and the economy[22]. We then analyze the impact of 23 Food System Measures (FSMs), individually and in packages. They include measures such as higher consumption of pulses, protection of biodiversity hotspots from land use change, increased manure recycling, minimum wages, and other measures that have been suggested for transforming the global food system towards better health, environment, and inclusion outcomes (Extended Data Table 1). Combining all FSMs in the context of the reference scenario SSP2 leads to the FST_{SSP2} scenario. We also assess the cross-sector impacts of 5 sustainability transformations outside the food system (CrossSector), such as more equitable economic growth and human development, energy transition towards renewables, and increased timber use as a construction material. Combining the FST with the CrossSector impacts defines our Food System Transformation in the context of a Sustainable Development Pathway (FST_{SDP}). All FSMs and CrossSector impacts are described in detail in Extended Data Table 1.

Our study expands on previous quantitative assessments[7,23–30] by extending the set of analyzed FSMs and measuring new outcome indicators, in particular on social inclusion. Our study innovates by conducting a multi-measure, multi-criteria assessment, covering 23 FSMs, 5 CrossSector transformations and their impact on 15 indicators within a single, consistent, quantitative framework. Simulating the effects of FSMs individually and in packages highlights specific synergies and trade-offs.

This integrated assessment is carried out using the open-source land and food system model MAgPIE[19], linked with a food demand model[2], the vegetation, crop and hydrology model LPJmL[31,32], the reduced-complexity climate model MAGICC[33], a dietary health model[7,34], an income distribution and poverty model[35] as well as with results from the macro-economy and energy system model REMIND[36]. We simulate the impact of each individual measure, as well as their interaction in packages focusing on five policy fields: (i) diets, (ii) livelihoods, (iii) biosphere, (iv) agriculture and (v) cross-sector impacts from transformations outside the food system. Our approach focuses on primary production of crop and livestock commodities and final food consumption, but does not cover measures targeting food environments or supply chains, like food processing, marketing or disposal. Further, the policy instruments and the political economy necessary to implement the measures[22] are not within the scope of this analysis.

Our assessment up to the year 2050 shows that each individual FSM creates trade-offs, but packaging of FSMs can enhance co-benefits and reduce trade-offs. Combining all measures within the food system achieves a comprehensive improvement of most outcomes relative to the reference scenario; but it also requires cross-sector transformations to create a sustainable food system that aligns with the 1.5°C climate target. The quantitative integration of our comprehensive multi-criteria analysis fills a gap in the literature, which usually looks at a much more limited set of measures and outcomes[37] and will provide a key input for upcoming regional and global assessments such as the Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).

Main

Our $BASE_{SSP2}$ reference scenario (SI S1.3) projects population growth to 9.4 billion people, reduced food insecurity but declining dietary health, general deterioration of the environment, declining absolute poverty and falling agricultural employment for the period 2020-2050.

Food security improves but dietary health deteriorates in the reference scenario

Diet-related health follows divergent trends (Fig. 1a-c, Extended Data Figure 1a-c). First, the number of people underweight falls from 730 to 640 million people, with the highest remaining prevalence in South Asia, and falling prevalence in Africa (Extended Data Figure 1). Second, in line with the nutrition transition towards energy-dense and nutrient-poor diets[2], the number of people affected by obesity increases from 848 to 1461 million, a conservative estimate compared to another projection[38]. In 2050, obesity is most prevalent in the Global North, with high levels also found in emerging economies in Latin America, East Asia and West Africa. Southern Africa and South-East Asia suffer the double burden of malnutrition, with high levels of under- and overnutrition. We find an increase in premature mortality due to dietary and metabolic health risks from 281 to 364 million life years lost per year, which is equivalent to a mean life loss per person rising from 3.6 to 3.8%, when divided by population. The highest rates of diet-related premature mortality are in the Global North, particularly in Eastern Europe, and the lowest in East, West and Central Africa; a geographical pattern mirroring the international consumption patterns of healthy and unhealthy food items[39].

Most global environmental indicators deteriorate in the reference scenario

Environmental indicators generally deteriorate in the baseline scenario, except for environmental water flow violations which stay constant (Fig. 1h-m, Extended Data Figure 1h-m).

Aggregating biodiversity change to the global scale remains a conceptual challenge due to the diversity of associated values[40]. Here, we use a set of different outcome indicators to capture the key drivers of biodiversity change related to the food system. The impacts of land-use change on biodiversity are mapped spatially using the *Biodiversity Intactness* Index (BII)[27]. Global land-use dynamics cause a continued decline of BII values until 2050. Expansion of agriculture particularly affects *BII* in Biodiversity *Hotspot Landscapes*, which are critical to global biodiversity conservation[41]. Loss of landscape heterogeneity also drives *BII* decline in *Cropland Landscapes*, implying a continued loss of biodiversity and critical ecosystem functions in cultured landscapes[42]. *Croparea Diversity* also declines, attributable to specializing in high-yielding crops with shorter rotations. It is highest in East and South Asia, as well as Central America. Further drivers of biodiversity change are captured by our indicators for nutrient pollution, climate change and unsustainable water use.

Nitrogen Surplus is a key indicator of the impacts of nitrogen pollution on air, water, soils and the atmosphere[43], causing harm to biodiversity, global health and the economy[44]. We here define them as the sum of nitrogen lost from croplands, pastures, animal waste management and natural vegetation. Our model estimates an increase from 245 to 303 Tg Nr/yr over the period 2020-2050. Pollution hotspots are found in China, India, Eastern Europe, the Corn Belt in North America and the Plata Basin in South America. Nitrogen pollution intensifies to 2050, particularly in India. Moderate pollution levels are also reached in Sub-Saharan Africa as its agricultural sector grows and intensifies.

GHG emissions from agriculture, forestry and other land use (AFOLU) slightly fall from 10.2 Gt CO_2 equivalents (CO_2eq; using GWP100) in 2020 to 8.6 Gt by 2050. Emissions are highest in densely populated areas, particularly in Asia, while re/afforestation compensates for many of the agricultural emissions in the Global North (Supplementary Figure 12). Combined with emissions from outside the land-use sector, these emissions from AFOLU induce a *Global Surface Warming* of 2.04 °C in 2050 compared to the reference period of 1850-1900, closest aligned with the Representative Concentration Pathway RCP6.0 (SI S2.2.7). Thus, despite integrating the Nationally Determined Contributions (NDCs), our reference scenario likely violates the temperature target of the Paris Accord even before 2050. The global climate model MRI-ESM2 used for this study shows the highest temperature increases in North America, North and East Asia and Australia.

The globally aggregated volume of Environmental Water Flow Violations[45] due to excessive water withdrawals by agriculture and other industries remains roughly constant in the reference scenario. In 2020, environmental flow violations are estimated to occur in the Middle East, Mediterranean, South and East Asia as well as the West Coast of the USA. By 2050, Southern and Eastern Africa as well as Eastern South America also show environmental flow violations.

Poverty is reduced, employment in agriculture strongly declines, and the share of agriculture in the global economy falls in the reference scenario

On social inclusion (Fig. 1.d-g, Extended Data Figure 1d-g), the reference scenario projects a reduction of the global poverty headcount of people living on less than 3.20 USD_{11PPP} per day from 2104 to 852 million people until 2050, largely due to economic growth in low-income countries. *Expenditure on Agricultural Products* - estimated as the annual value of agricultural commodities that are used for food, but excluding the substantial value-added in processing and marketing[46] - increases from 498 to 576 USD_{05MER} per capita due to more diverse and resource-intensive diets, with strongest increases in Sub-Saharan Africa and South Asia. Our model projects improvements in agricultural labor productivity and wages (in the model represented by the mean nominal hourly labor cost per worker), with a concurrent decline in agricultural employment from 770 to 461 million people by 2050, most strikingly in Sub-Saharan Africa and Asia.

The food system is embedded in the wider economy (Fig 1n,o), delivering non-food materials as *Bioeconomy Supply*, and requiring labor and capital in agricultural production as reflected by *Production Costs*. The *Bioeconomy Supply* of non-food materials and energetic use increases slightly, and is located mostly in the Global North and Brazil. Agricultural production costs grow slower than the economy as a whole in the period from 2020 to 2050 (39% vs 116%) such that the relative share of agriculture in total Gross World Product declines.

Other baseline scenarios are also not in line with sustainable development

Besides the $BASE_{SSP2}$ reference scenario, we also simulate the other four SSP baseline scenarios (Extended Data Figure 2), which diverge with respect to the central socio-economic assumptions (SI S1.3). Despite modest improvements with respect to individual outcomes, our study provides supporting evidence that baseline trends will not improve food security sufficiently[29], nor obesity[38], health[34], biodiversity[27], nitrogen pollution[47], water[7], greenhouse gas emissions[8], or employment[48]. Only with respect to poverty and agricultural wages, two of the five baselines scenarios ($BASE_{SSP1}$ and $BASE_{SSP5}$) show substantial improvements until 2050 as a consequence of income growth and reduced inequalities[35]. Nonetheless, the largely undesirable and unsustainable outcomes across baseline scenarios suggest that a deeper, more deliberate, multi-dimensional transformation of the food system and of people’s access to food will be necessary to ensure sustained improvements in health, environment, and social inclusion over the 21st century.

Each of the food system measures generates co-benefits and trade-offs

To improve health, social inclusion, environment, and economic outcomes, we investigate the impact of 23 discrete Food System Measures (FSMs), described in Extended Data Table 1. We find that all individual FSMs come with co-benefits and trade-offs across outcome indicators (Figure 2). When the FSMs are combined as packages along the major policy fields, the outcome profiles of the individual measures overlap, often enhancing co-benefits and reducing trade-offs. Packaging FSMs together can develop interaction effects that further reinforce or dampen the combined impact relative to the sum of individual impacts (Extended Data Figure 3).

The *Diets* package develops generally positive synergies across 12 indicators. The strongest co-benefits stem from FSMs that reduce the resource-intensity of diets (LowFoodWaste, LowMonogastrics, LowRuminants, HalfOverweight FSMs). They do, however, reduce *Agricultural Employment*. In contrast, dietary shifts that scale up consumption of healthy food items (HighLegumes, HighVegFruitsNuts, NoUnderweight FSMs) increase employment but show modest trade-offs with some environmental indicators as well as *Expenditure on Agricultural Products*. As a package, only the trade-off with employment remains. With respect to *Croparea Diversity*, the dietary shifts even lead to positive synergies (Extended Data Figure 3). Overall, the package creates co-benefits with respect to health, environment, and poverty, with a trade-off in the case of reduced employment

The *Livelihood* package improves 9 indicators, with major trade-offs for *Expenditure on Agricultural Products*, and *Agricultural Employment*. The *LibTrade* FSM, shifting from historical trade patterns to more open trade allows more efficient allocation of water, land and fertilizer. It thereby leads to modest environmental improvements. Minimum wages (*MinWage* FSM) improve livelihoods, but also drive up *Expenditure on Agricultural Products,* and lead in our model to a decrease in employment due to intra- and inter-regional capital-labor substitution (without accounting for demand-increasing income redistribution effects, SI table X). These job losses are reinforced when trade is opened at the same time due to production displacement to more capital-intensive world regions.

The *Biosphere* package generates more heterogeneous outcomes. Strong benefits occur for BII, environmental water flow violations and *GHG Emissions*, as water and land resources are protected by these FSMs. Trade-offs exist with respect to *Croparea Diversity* as crop production on the remaining land needs to be intensified in the absence of demand-side reductions, leading to shorter crop rotations and also higher *Nitrogen Surplus*. Moreover, *Expenditure on Agricultural Products* rise, as do *Poverty* rates because of increasing costs of agricultural production and consequently of food products .

In the *Agriculture* package, the individual FSMs often have complementary environmental benefits and trade-offs. The FSM *LivestockManagement* substantially mitigates GHG, but higher feed energy efficiency, via shifts from roughage to concentrate feeds, results in more agglomerated and less diverse croplands and higher irrigation water withdrawals. The FSMs *CropRotations* improves *Croparea Diversity* at the cost of increased land expansion reflected by a decline of the *Biodiversity Intactness* indicators, while the FSM *Landscape Habitats* does the inverse as it increases land scarcity by limiting cropland agglomeration. The FSM *NitrogenEff* strongly reduces *Nitrogen Surplus* and creates additional employment, but at the higher costs that also get reflected in the *Expenditure on Agricultural Products*. However, for the *Environmental Water Flow Violations*, the individual impacts of the FSMs are even reinforced when the FSMs are packaged, since longer crop rotations and shifts towards more concentrate-based livestock systems result in higher cropland scarcity. Within the package, this land scarcity is not resolved through cropland expansion as this is disincentivized by the *SoilCarbon* FSM;

instead irrigation is expanded. Generally, trade-offs are seen with respect to *Production Costs*, *Expenditure on Agricultural Products* and *Poverty*, while *Employment* increases strongly.

An extended coverage of processes connecting measures and outcome indicators leads to novel insights

Our quantitative results generally corroborate the evidence found in the qualitative multi-criteria synthesis of the IPCC[49,50](see Fig 17.1.), in particular with regard to the broad co-benefits of dietary change. However, we newly quantitatively identify a potential trade-off with *Agricultural Employment*. While the IPCC[49] finds strong environmental co-benefits of methane (CH_4) and nitrous oxide (N_2O) mitigation as well as carbon sequestration, we find more heterogeneous outcomes of *Agriculture* FSMs with both environmental trade-offs and co-benefits. Further, we newly quantify major novel *Employment* opportunities in mitigation activities in agriculture, and quantify their undesirable trade-offs with *Poverty*. The IPCC[49] finds clear benefits of biosphere protection and restoration for life on land and water. While our Biosphere package also finds an improvement in Biodiversity Intactness and Environmental Water Flows, we also observe negative environmental outcomes for *Croparea Diversity* and *Nitrogen Surpluses* due to intensification of the remaining agricultural land.

Such divergent evaluations can be explained by the different coverage of underlying processes. Supplementary Data File 1 documents the major processes within our model framework that connect the 23 FSMs and the 5 CrossSector transformations with the 15 outcome indicators and discusses further important processes that exist in reality but are not captured by our modeling. For instance, we do not cover potential yield improvements by higher soil carbon sequestration in our SoilCarbon FSM, and avoided deforestation, reforestation and timber production (*REDD+, TimberCities FSMs*) does not increase *Agricultural Employment,* as our model does not consider employment in the forestry sector.

Packaging all food system measures curtails trade-offs

Packaging together all 23 FSMs, the FST_{SSP2} scenario improves outcomes for 13 of 15 indicators compared to $BASE_{SSP2}$ (Figure 1, 2). The integration across and within policy fields reveals clear complementarities (Extended Data Figure 3): While the *Diets* and the *Livelihoods* packages reduce agricultural employment, mitigation activities within the *Agriculture* package increase it. Production costs are increased by the *Agriculture* package, but decreased by the *Diets* package. *Water scarcity*, increased by the *Agriculture* package, is mitigated as environmental water flows are protected by the *Biosphere* package. Finally, the intensification of agriculture induced by the *Biosphere* package is counterbalanced by resource-efficient management in the *Agriculture* package.

Health and environmental indicators, both globally and regionally (Extended Data Figure 4), mostly improve compared to $BASE_{SSP2}$. When comparing the FST_{SSP2} scenario to the world's current state in 2020 ($BASE_{SSP2}$), only global warming deteriorates (Extended Data Figure 2). Accounting for the uncertainties in the climate system's response to present and future emissions[33], the FST_{SSP2} scenario will be 1.86°C (median estimate) warmer in 2050 than the 1850-1900 reference period, with a 90% probability that the 1.5° target will be exceeded by that year. Over a longer time-horizon, by 2100 there is a 59% probability that the 2° target is transgressed, in contrast to a 95% probability in $BASE_{SSP2}$ (SI S2.2.7). This demonstrates the large contribution a food system transformation can make for climate mitigation, even in the absence of an energy transition; in the FST_{SSP2}, AFOLU emissions turn net-negative by 2035 as forests sequester carbon.

Despite the high costs of mitigation and increased consumption in previously food-insecure countries, the FST_{SSP2} scenario does not increase absolute global *Poverty* and even leads to a modest reduction compared to $BASE_{SSP2}$ in 2050. Reduced food consumption in richer countries together with trade liberalization decreases food prices and dampens the increase in *Expenditure for Agricultural Products*. Simultaneously, higher wages coupled with the recycling of revenues from CO_2 taxation increase real incomes and reduce poverty in many low-income countries. Yet, poverty remains nearly as widespread a phenomenon in the FST_{SSP2} as in the reference scenario. Although new employment opportunities arise from mitigation activities in agriculture, it is not enough to compensate for the reduced employment attributable to less resource-intensive diets. Thus, *Agricultural Employment* declines by 76 million people relative to $BASE_{SSP2}$.

The food system transformation must be embedded in a broader sustainability transformation

Our investigation of the cross-sector impact of five sustainability transformations outside the food system (*CrossSector* package, Figure 2) indicates that the food system transformation must be embedded within an economy-wide sustainable development pathway[25] to halt global warming, reduce absolute poverty, ease structural change, and achieve further sustainable development goals[25]. Slower population growth stemming from improved socio-economic development (*Population*), with only 8.9 billion people by 2050, reduces pressure in agricultural markets and environmental degradation. More sustainable human development, including faster and more equitable economic growth in LICs (*HumanDevelop*), reduces *Undernutrition* and *Poverty*, but increases *Obesity* and *Expenditure on Agricultural Products*. Due to increasing labor productivity and a higher deployment of capital, agricultural employment in *HumanDevelop* is even lower than in $BASE_{SSP2}$. The additional jobs created by the provision of agricultural materials for the bioeconomy (EnergyTrans and Bioplastics scenarios) do not create sufficient alternative employment within agriculture to compensate for this. However, as the global wage index is 74% higher in the *CrossSector* package than in the reference scenario $BASE_{SSP2}$, the remaining jobs provide better livelihoods. The sustainable transformation of the energy system (*EnergyTrans*) reduces global warming to 1.73°C by 2050, with only a 20% chance of exceeding 2°C in 2100, while the demand for second generation bioenergy remains low before the second half of the century and therefore has low impacts on the food system until 2050 in our model assessment.

A sustainable food system is possible, but requires a transformation at massive scale and speed

The Food System Transformation in the context of an economy-wide sustainable development pathway ($\text{FST}_{\text{SDP}} = FST_{SSP2} \cup \text{CrossSector}$) illustrates the possibility and quantitative consistency of a global food system that nourishes a healthy population, provides affordable food with a low environmental footprint and improves livelihoods in agriculture. The FST_{SDP} simultaneously improves 14 out of 15 key outcome indicators. It aligns with SDG2 in ending hunger and the World Health Organization target to halt the rise of obesity[4]. Mortality is reduced by 261 million life years per year in 2050, the degradation of the biosphere is halted and the pressure on biodiversity is reduced compared to today. Considering the climate model uncertainty, the emission trajectory of FST_{SDP} keeps global warming below 1.5° with a 46% probability and below 2° with a 91% probability by 2050, with peak warming occurring before 2040 (SI Supplementary Figure 13).

In line with previous studies[7,25,26,43,51], we find that it is very challenging to meet the planetary boundary for nitrogen pollution. Nitrogen surpluses from agricultural soils (here excluding surplus from manure management and natural soils for comparison purposes with the most recent boundary estimate[43]) are reduced drastically from 195 Mt Nr in the reference to 68 Mt Nr in the FST_{SDP} scenario. But these still exceed the planetary threshold of 57 Mt Nr[43] as well as critical regional thresholds, in particular in hotspots like China and India.

The agricultural labor force is much better paid, and more equitable human development outside of the food system ensures that the absolute poverty headcount falls by 627 million to 225 million. Despite considerable mitigation costs in agricultural production, plant-based consumption patterns coupled with less food waste reduce *Production Costs* globally in the FST_{SSP2} and FST_{SDP}.

Comparing FST_{SDP} and FST_{SSP2} shows that a sustainable food system requires transformations in the rest of the economy, including most importantly reducing GHG emissions in the energy sector, reducing poverty to make healthy food affordable for all, increasing demand for bio-based materials and fuels, and absorbing the excess agricultural labor force caused by structural changes in the food system.

The FST_{SDP} pathway further highlights that these changes must occur rapidly in order to achieve a sustainable food system by 2050. This quantitative pathway helps to identify the necessary changes and break them down into concrete measures and intermediate milestones which can then serve to benchmark progress in different parts of the food system (SI S2.3). Milestones for 2030 include a decrease in animal-based product consumption by 39% in current high-income regions (HIRs) and in middle-income regions (MIRs) by 9%. The production of fruits, vegetables and nuts in contrast has to be scaled up by 27% globally. Net-zero land use change emissions should be reached before 2030, while total AFOLU emissions should be net-zero before 2040. By 2040, 16 million hectares of wetlands should be rewetted. Global soil nitrogen uptake efficiency should rise from 57% in 2020 to 69% by 2040. To encounter structural change, the social systems and the job markets in industry and services need to absorb 312 million people by 2040 that formerly worked in agriculture, predominantly in low-income regions.

Some tradeoffs remain unresolved

Packaging measures helps to reduce trade-offs substantially. However, some undesirable outcomes remain.

The largest remaining potential trade-off is the reduction in agricultural employment in the FST_{SDP} by an additional 157 million people on top of the reduction by 309 million in the period 2020-2050 in the $BASE_{SSP2}$ reference scenario. However, the desirability of this outcome is uncertain. Higher labor productivity resulting in lower employment and higher agricultural wages can be seen as a coherent and necessary outcome of economic development[52]. On the other hand, the speed of structural change may exceed the adaptive capacity of individuals as well as social and political institutions[48]. Our study shows that new employment opportunities in agro-environmental practices and the bioeconomy can only slow down structural change, but that the largest part of the surplus workforce needs to be absorbed outside the agricultural sector. This can be facilitated e.g. by providing retraining or mobility schemes, cash transfers for older workers who may find no alternative livelihoods, or promoting hybrid business models such as direct marketing, on-farm processing or agri-tourism[53–55].

Moreover, regional trade-offs or displacement effects exist. For example, while the *Biodiversity Intactness* generally improves, there are some regions where it deteriorates (Figure 3). Similarly, while the minimum environmental water flows are protected in the FST_{SDP}, displacement effects from water protection create additional moderate water stress in several regions that were previously unaffected (Figure Extended Data Figure 1). Rising regional production costs are not necessarily undesirable for a region as they can also reflect an increase of production, for example in Brazil or Northern Asia.

From scenarios to a shared vision and its implementation.

Our assessment shows that a comprehensive food system transformation can achieve win-win outcomes for most people. While a positive vision and its detailed elaboration are crucial for guiding transformative social change[13–15], the development of a vision should not only be inclusive in its outcome, but also participatory in problem framing, solution design and prioritization[56]. Our scenarios are a contribution to this evolving societal debate about a sustainable and socially desirable global food system, supporting the building of a shared vision by the wider public[13,14]. Our study design - allowing for multi-measure and multi-criteria comparisons - facilitates such an open and flexible process.

While our study investigates concrete measures for the food system transformation, we do not assess the wide range of possible policy instruments that could be used to implement them[22], which would have additional consequences. First, we do not include the transaction costs of policy-making, monitoring, and enforcement. Second, depending on their type and design, policies can also lead to very different distributional outcomes. For instance, both a subsidy or a tax can incentivize the implementation of a measure, but with diverging effects on farmers and general taxpayers. Third, the implementation of policies may be limited by the absence of necessary institutions and governance capacity. Our quantitative scenario assessment does however provide benchmarks for the necessary ambition of policy packages[22]. By applying a holistic perspective across health, environment, and inclusion, our study facilitates a comprehensive public dialogue on sustainable food system transformation.

Declarations

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Author contributions

BLB, HLC, AP, FB and FH designed the study

BLB, JPD, FH, MSp, CM, ZN, BS, JS, JH, JL, DMC, IW, MSt, DL, MC, XW, PvJ, KK, AM, EMB, FB, VS, AP, HLC developed the model framework and output routines.

FB, FH, DMC, MC, ZN, CM, MSp, DL, BS, JH provided the model runs.

FH, DMC, BLB, MC, PvJ, FB designed the figures.

BLB, FB, FH, HLC, DL, MC, RK, CH, AP analyzed the results.

PF, JPD provided software engineering solutions and technical support.

All authors analyzed the results.

BLB, DMC, MC, MSp, CM, DL, ZN, JS, FH, IW, PvJ, AM, FB, RK, CH wrote the manuscript with contributions and comments from all coauthors.

Data availability

Model runs and results shown in this paper are available under the Creative Commons Attribution license CC-BY-4.0 and archived at https://doi.org/10.5281/zenodo.7924160

Code availability

The MAgPIE code, including the food demand model, is available under the GNU Affero General Public License, version 3 (AGPLv3) via GitHub (https://github.com/magpiemodel/magpie, last access: 5 May 2023). The release (version 4.6.6) used in this paper[57] can be found via Zenodo (https://doi.org/10.5281/zenodo.7920802). The technical model documentation is available under https://rse.pik-potsdam.de/doc/magpie/4.6.6/ (last access: 5 May 2023).

The LPJmL code is available under the GNU Affero General Public License, version 3 (AGPLv3) and the code used here to generate inputs for MAgPIE can be found at Zenodo.org (https://doi.org/10.5281/zenodo.7912370).

The REMIND code is available under the GNU Affero General Public License, version 3 (AGPLv3) via GitHub (https://github.com/bs538/remind/tree/SDP_runs).

Model documentation of the health model is available in the appendix and in Springmann et al[58], model documentation of the poverty model in Soergel et al[35].

For processing the m4fsdp package[59] has been used which is available at https://doi.org/10.5281/zenodo.7899913 .

The code used to run MAGICC is available at https://gitlab.com/magicc/2022-fsec-integration.

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Methods

Modeling Framework and study design

This assessment was carried out by the Potsdam Integrated Assessment Modeling framework (PIAM), which is a cluster of models that exchange information not during runtime but from consistent stand-alone simulations (soft-link). For this study, the open-source land and food system modeling framework MAgPIE[19,77] is the central model. It is linked with an open-source food demand model[2], the open-source vegetation, crop and hydrology model LPJmL (Lund-Potsdam-Jena model with managed Land) [31,32], the reduced-complexity climate model MAGICC [33,78,79], a poverty distribution model[35] as well as the open-source macro-economy and energy model REMIND[36]. The food demand model is further linked with a dietary health model[58,80]. Extended Data Figure 5 lists the linkages between the individual models, which parameters are exchanged, and which outcome indicators are estimated by which model.

The modeling framework was run for a total of 40 scenarios, including the reference scenario SSP2, the 4 other baseline SSPs, a run for each of the 23 FSMs and 5 CrossSector measures in isolation, 5 packages of measures, the $\mathrm{FST}_{\mathrm{SSP2}}$ and the $\mathrm{FST}_{\mathrm{SDP}}$. The implementation of the FSMs and the definition of the outcome indicators are described in the Extended Data Tables 1+2, as well as in the Supplementary Data file 1.

MAgPIE

The central component of this modeling framework is the land and food system model MAgPIE (Model of Agricultural Production and its Impact on the Environment)[19,77], which is in itself a modeling framework with multiple hard-coupled modules (Extended Data Figure 4). The open-source model code and documentation for the version 4.6.6 used in this study are available online[57].

The model simulates agricultural markets for 19 different crop groups, 8 processed plant-based product groups (sugar, oil, alcohol, oilcakes, molasses, ethanol, brans, brewers' and distillers' grains), 5 livestock food groups (ruminant meat, milk, monogastric meat, poultry meat, eggs), three types of crop residues (cereal straw, fibrous and non-fibrous residues), grass, and two forestry products (timber, fuelwood). Final demands include food demand (see Food demand model), material demand, and bioenergy demand[81,82] (SI section S1.1.2). Livestock products require feed[69,70] (SI section S1.1.3), processed products require primary products (SI section S1.1.4), and crop production requires seeds. Global production needs to meet global demand, with trade between world regions balancing regional production and demand (SI section S1.1.5). Crop, grass, and forestry production require land for cultivation (SI section S1.1.6). Land allocation is driven by the cost-effectiveness of different land uses (cropland, pasture, built-up land, forestry[83], forest, other land) across space, as well as land conversion costs (SI section 1.1.8). Land Use Change (LUC) causes CO_2 emissions from the clearing of vegetation[84] (SI section 1.1.11) and changes the BII value of the land[27] (SI section 1.1.9). Soil carbon levels are also negatively affected by LUC, but also depend on agricultural management (SI section 1.1.10). Irrigated production requires water and irrigation infrastructure, which can also be expanded into new areas[45] (SI section 1.1.12). Crop and grass production requires nitrogen, which needs to be provided through the recycling of organic materials, biological fixation, inorganic fertilizers, or soil depletion[51] (SI section S1.1.7). Agricultural production causes non-CO_2 GHG emissions (SI section S1.1.11) that include CH4 from enteric fermentation, water management of rice fields, and manure management. N_2O emissions derive from fertilization of crop and pasture soils as well as animal waste management and residue burning[51]. Emissions can be mitigated using technical mitigation measures[67] (SI section S1.1.11).

To find a plausible pathway for the future, the model minimizes total costs while being subject to a number of biophysical, technological, and socio-economic constraints. Total costs include factor costs for labor and capital for agricultural production (see section 1.1.6), investment costs into yield-improving technologies and management practices[85], land expansion costs, fertilizer costs, as well as, in some scenarios, taxes for environmental pollution. Another set of costs is internal to the model as their markets are represented explicitly in the model. This includes, for example, the costs for feed and seed; land rents, which derive from the scarcity of land and land expansion costs; and the costs for nutrients from crop residues and manure.

Agricultural employment depends on the factor requirements for agriculture, the labor-capital share, labor productivity, and weekly working hours (see section 1.1.6).

Agricultural prices, which are required for estimating *Expenditure on Agricultural Products*, can be derived as the Lagrange multiplier of the food demand equation, providing the marginal costs of supplying the agricultural products for one additional unit of food in a given world region.

Food demand model

The food demand model[2] estimates a consistent set of scenarios for food intake, food waste, dietary composition, the distribution of body weight along five body mass index (BMI) classes and body height on a country level. Shifts in dietary composition over time are projected for four main food groups, i.e., animal-source foods, empty calories from oils, sugar, and alcoholic beverages, staple foods, as well as calories from fruits, vegetables, and nuts. A further split to the 25 food items in MAgPIE is implemented according to observed relative shares on the country level. Anthropometric and intake estimates differentiate between males and females, as well as between different age groups. Drivers of the model are the demographic composition of a population by age and sex, physical activity levels, the starting distribution of body height, and the per-capita income as a proxy for the socio-economic development state of the food system.

Historical food waste (defined as household-level food waste and food losses in gastronomy and retail[86]) is derived as the difference between FAO food calorie supply and the food calorie intake estimated based on observed body weight, physical activity levels, age, and sex. For baseline projections, the ratio of food calorie supply and food intake is calculated using a regression with per-capita income[2]. Since we estimate food intake and food waste top-down only from the energy balance, the composition of food waste with respect to different products was inferred from food-group specific waste estimates[87].

For diet FSMs, different assumptions are made for the exogenous calculation of food waste, diet composition, or calorie intake (see Extended Data Table 1). For scenarios with these FSMs, we assume a gradual transition of the endogenously estimated components of food demand to the scenario-specific parametrization of food waste, food intake, and diet composition until 2050. For all FSMs, body weight, physical activity, and caloric intake remain consistent along an energy-balance approach. Weight FSMs assume an increase or decrease of intake in line with the targeted body weight. FSMs that change dietary composition (such as minimum consumption of fruits and vegetables or maximum consumption of animal products) balance intake by a reduction or increase of staple crops (cereals and roots) such that total intake stays constant.
Within the architecture of soft-linked models, the country-level results of the food demand model are passed on to MAgPIE, the health model, and the poverty model.

Crop, vegetation, and hydrology model (LPJmL)

The Lund Potsdam Jena Model managed Land (LPJmL) is a global dynamic vegetation, hydrology, and crop model, dynamically computing soil and vegetation dynamics in natural and managed (croplands, grasslands, biomass plantations) ecosystems, explicitly accounting for water, carbon, and nitrogen fluxes within and between ecosystems[31,32]. For this analysis, LPJmL computes crop yields for twelve different annual field crops for purely rainfed and fully irrigated production systems as well as corresponding irrigation water requirements, carbon stocks of potential natural vegetation, and river discharge as an indicator of freshwater availability. All scenarios include CO_2 fertilization. CO_2 fertilization is still uncertain in magnitude, but experimental evidence shows substantial yield-increasing and water-saving effects[88]. Nitrogen limitation of crop growth is ignored here because economic decision-making on production intensity and corresponding nitrogen input requirements is accounted for in the MAgPIE model. Crop yields and irrigation water requirements are computed with the nitrogen version of LPJmL[32,89,90], while natural vegetation dynamics, including carbon stocks and freshwater availability, are computed with LPJmL version 4[31].

As such, crop yields, water requirements, carbon stocks, and water availability were computed ex-ante for specific climate scenarios, which could then be selected according to the projected global mean temperature (see Climate Models section).

Health Model

We used a global risk-disease model with country-level detail to estimate the impacts that dietary changes related to the different food-system interventions could have on disease mortality[58,80]. The model uses a comparative risk assessment method that relates changes in risk factors, such as reductions in the consumption of fruits and vegetables, to changes in cause-specific mortality, such as cancer and coronary heart disease[91]. The same concept forms the basis of the Global Burden of Disease project that tracks the impacts of different risk factors on mortality and morbidity in different regions and globally[92].

The comparative risk-assessment model used here included eight diet and weight-related risk factors and five disease endpoints. The risk factors were high consumption of red meat, low consumption of fruits, vegetables, nuts, and legumes, as well as being underweight, overweight, and obese, the latter of which are related to changes in energy intake. The disease endpoints were coronary heart disease (CHD), stroke, type-2 diabetes mellitus (T2DM), cancer (in aggregate and as colon and rectum cancers), and respiratory disease.

We used publicly available data sources to parameterize the comparative risk analysis. We adopted relative risk estimates that relate changes in risk factors to changes in disease mortality from a meta-analysis of prospective cohort studies[93–99]. Age-specific mortality and population data were adopted from the Global Burden of Disease project[100], and baseline data on the weight distributions of countries were adopted from a pooled analysis of population-based measurements undertaken by the NCD Risk Factor Collaboration[101]. A detailed model description is provided in the supplementary information file 1 and in Springmann and colleagues[58,80].

Climate models

Our modeling framework establishes consistency between global warming outcomes and biophysical climate impacts using a reduced complexity climate model to estimate the global warming outcome. This informs the selection of pre-calculated high-resolution daily weather projections under climate change from a General Circulation Model (GCM).

We employed the reduced-complexity climate model MAGICC (v7.5.3)[33,78,79] to generate a probability distribution of projected global warming (S2.2.7, Figure 13) using greenhouse gas emissions from the land system (MAgPIE) and the rest of the economy (REMIND). We ran MAGICC with a probabilistic setup following the IPCC's latest WG1 report[102] (see Cross-Chapter Box 7.1 in Chapter 7 of AR6 WG1). For emissions not included in REMIND-MAgPIE (e.g., Montreal Protocol species), we followed methods from the latest WG3 report[103,104]. As input to MAGICC, we combined AFOLU emissions from MAgPIE (CO_2, CH_4, N_2O) with non-AFOLU emissions (e.g., energy, transport, industry, waste) from prior REMIND scenarios (see REMIND section), ensuring coherence between bioenergy demand and energy transformation levels across the modeled scenarios. For scenarios without a matching REMIND scenario (specifically SSP3, SSP4, and SSP5 baselines), we do not report global surface temperatures.

To harmonize the global warming outcome from MAGICC with high-resolution weather data under climate change that is required to run LPJmL, we identified the Representative Concentration Pathways (RCP)[105] that had the smallest temperature deviation for years 2050 and 2100, focusing on the MRI-ESM2 runs within the CMIP6 model database, for each scenario's warming trajectory (see S2.2.7, Figure 11). We chose MRI-ESM2[106] because it provided a large set of simulations for different RCPs within the CMIP6 ScenarioMIP[107]. We use a single General Circulation Model (GCM) because climate impacts are not in the focus of this study. This process was robust to varying the RCP used in the initial run, as the second-order feedback of climate impacts on emissions is small.

This process resulted in our primary scenarios ranging from RCP1.9 (FST_{SDP}) to RCP6.0 ($BASE_{SSP2}$). For scenarios based on SSP 3, 4, and 5, complementary REMIND scenarios were unavailable, so we used the standard RCP7.0, RCP4.5, and RCP8.5 climate impacts, respectively. These scenarios, however, mainly served the purpose of sensitivity analysis and are not prominently featured in our analysis.

Based on this mapping, LPJmL receives daily weather projections from the MRI-ESM2[106] model's contribution to the CMIP6 ScenarioMIP[107], which were made available in bias-corrected form by the ISIMIP project Phase 3[108,109]. Atmospheric CO_2 trajectories are taken from the corresponding SSP-RCP combinations[107].

Poverty Model

A distributional model[35]is used to create projections of income distribution and poverty rates. The model starts by constructing baseline lognormal income distributions from average incomes and scenario assumptions for the Gini coefficient[110], a measure of income inequality. Any increased *Expenditure on Agricultural Products* stemming from implementing FSMs, if applicable, is translated into their impact on average real incomes and inequality levels based on an empirical estimation of food expenditure-income elasticities. To better represent the tails of distribution relevant to poverty, the new average incomes and Gini coefficients are then fed into a regression-based model fit to recent World Bank poverty and inequality data to derive scenario projections for future poverty headcounts, accounting for the effect of potentially increased food prices.

Using the partial-equilibrium model MAgPIE, we need to safeguard macroeconomic consistency when investigating poverty effects. Increased production costs for food items due to higher labor and capital requirements get reflected in higher *Expenditure on Agricultural Products* and lower real incomes of the model. In scenarios where food expenditures rise due to taxes (the CO2 tax in the FSMs *REDD+*, *PeatlandRewetting*, *SoilCarbon* and the penalty for violating rotational rules in the *CropRotations* scenario, as well as packages including them), the generated tax revenues are redistributed to citizens. We assume a distributionally neutral redistribution of tax revenues (broadly similar to a reduction of the value-added tax) but do not include any specific pro-poor redistribution policies (discussed here[35]). Similarly, we take into account that the wage increases from the MinWage scenario do not only increase prices but also have an income effect. We assume again a neutral distribution to the entire population as our income data does not allow us to distinguish agricultural income from other sources of income. As such, our MinWage scenario mainly reflects the regressive effect of higher food prices on consumers, but not that mainly low-income households would benefit from a minimum wage in the agricultural sector.

Macro-Economy and Energy model (REMIND)

We use the global multi-regional energy-economy-climate model REMIND Version 2.1.3 for our analysis[36]. REMIND is open source and available on GitHub athttps://github.com/remindmodel/remind. The technical documentation of the equation structure can be found at https://rse.pik-potsdam.de/doc/remind/2.1.3/. In REMIND, each single region is modeled as a hybrid energy-economy system and is able to interact with the other regions by means of trade. The economy sector is modeled by a Ramsey-type growth model, which maximizes utility, a function of consumption. Labor, capital, and end-use energy generate the macroeconomic output, i.e., GDP. Population, labor productivity growth, and educational attainment are exogenous assumptions taken from the SSPs[71,111]. The produced GDP covers the costs of the energy system, the macroeconomic investments, the import of a composite good, and consumption. The energy sector is described with high technological detail.

REMIND provides the bioenergy demand for MAgPIE and the anthropogenic emissions for all sectors except for AFOLU for the MAGICC climate model (see also SI S1.2). For computational reasons, we did not couple the REMIND model and the MAgPIE model directly within this multi-scenario assessment but relied on existing runs of this well-established model ensemble[25]. For the SSP baseline scenarios and all transformations targeting land use in isolation, we assume that the energy transformation meets current nationally determined contributions, but no other progress is made in limiting emissions. In the *EnergyTrans* measure, we assume a robust energy transformation, such that a carbon budget of 900 Gt CO_2 from 2011 (610 Gt CO_2 from 2018) until the time of peak warming is not exceeded, based on the SSP2 900Gt scenario ofa sustainable development pathway[25](see SI section 1.2). In the CrossSector and FST_{SDP} scenarios, we use the SDP 900 Gt scenario, which achieves the same target with a more sustainable general economic development, e.g., with respect to population growth. Both the non-food system emissions as well as the bioenergy demand are consistent with this 900 Gt budget (see also SI S1.2).

We use a different, lower carbon price trajectory (carbon budget of 1300 Gt CO_2[25]) for the food system FSMs that require a carbon price, *REDD+*, *SoilCarbon,* and *PeatlandConservation*, in order to avoid unnecessarily high tax payments and food price changes at a tax rate where mitigation is saturating. As such, the two different tax rates ($185USD_{05MER}/tCO_2$ in AFOLU and $494USD_{05MER}/tCO_2$ in other sectors in the year 2050 in the FST_{SDP} scenario) diverge from the theoretical allocation optimum of a uniform carbon price; as we estimate global warming ex-post and keep consistency between the energy-scenario and bioenergy demand, our scenario remains biophysically fully consistent.

References Methods

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Figures

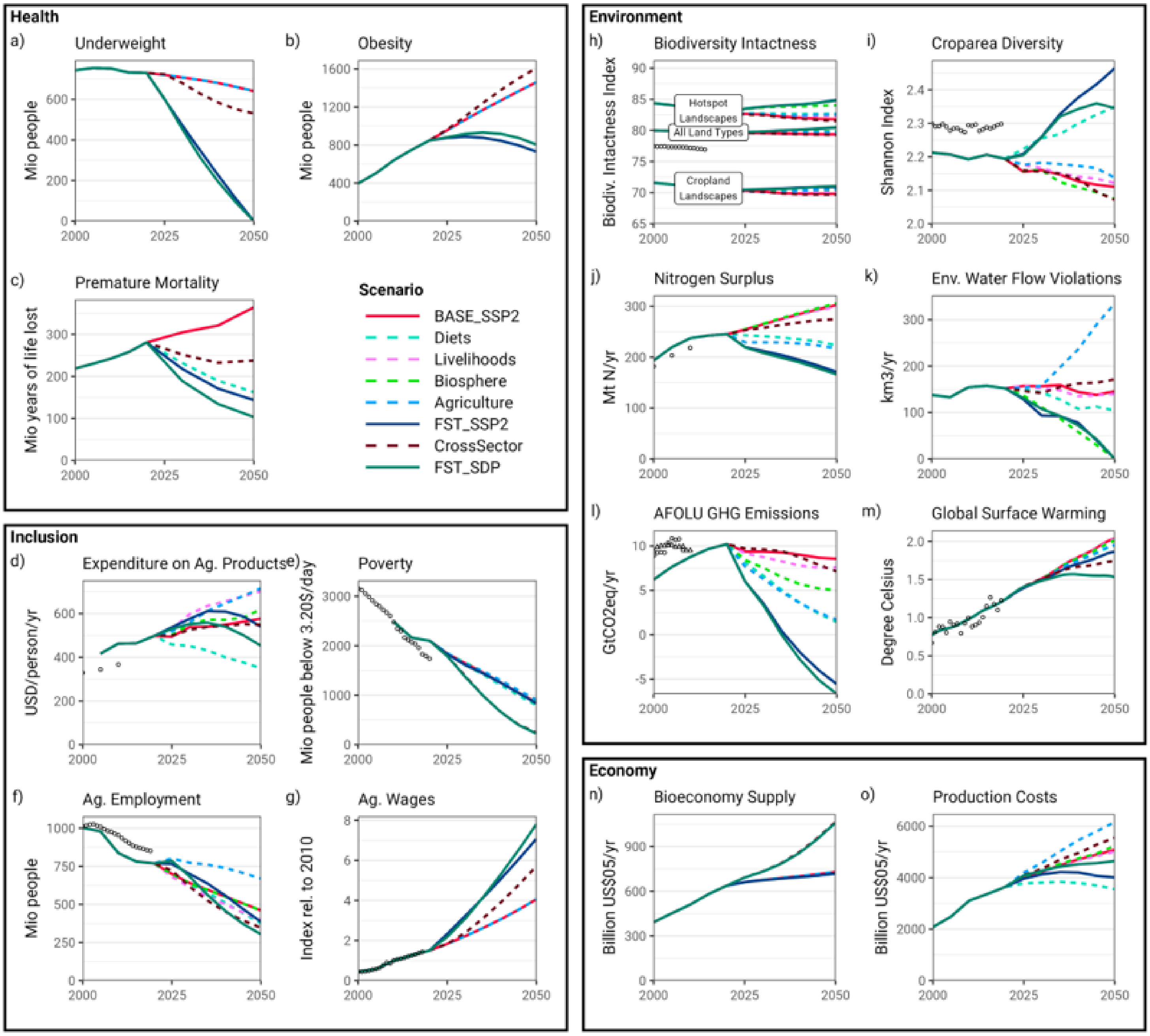

Figure 1

Scenarios for 15 food system outcome indicators. BASE$_{SSP2}$ (red line) describes a middle-of-the-road scenario. The Food System Transformation (FST$_{SSP2}$, blue line) describes a scenario that combines four packages of food system measures targeting healthy diets (Diets), livelihoods (Livelihoods), biosphere integrity (Biosphere), and agricultural management (Agriculture). If the cross-sectoral impacts of sustainable transformations in other parts of the economy (CrossSector) are added, we arrive at a Food System Transformation in the context of a sustainable development pathway (FST$_{SDP}$, green line). All outcome indicators are described in Extended Data Table 2, historical data points (dots) are described in SI S2.1.

Relative change
best
better
none
worse
worst

		Health			Environment							Inclusion				Economy	
		Underweight Mio people	Obesity Mio people	Premature Mortality Mio years of life lost	Cropland Landscapes Biodiv. Intactness Index	Hotspot Landscapes Biodiv. Intactness Index	Croparea Diversity Shannon Index	Nitrogen Surplus Mt N/yr	Env. Water Flow Violations km3/yr	AFOLU GHG Emissions GtCO2eq/yr	Global Surface Warming Degree Celsius	Expenditure on Ag. Products USD/person/yr	Poverty Mio people below 3.20$/day	Ag. Employment Mio people	Ag. Wages Index rel. to 2010	Bioeconomy Supply Billion US$05/yr	Production Costs Billion US$05/yr
	BASE_SSP2	640	1461	364	69.8	81.8	2.11	303	146	8.6	2.04	576	852	461	4.06	730	5084
Diets	**Diets**	0	730	163	70.46	82.67	2.35	222	104	1.4	1.94	350	796	376	4.06	718	3557
	LowProcessed			318	69.86	81.85	2.09	303	139	8.5	2.04	540	844	462	4.06	731	4749
	HighLegumes			340	69.7	81.73	2.14	301	154	8.7	2.04	592	857	462	4.06	724	5164
	LowMonogastrics			356	70.01	82.33	2.17	277	125	7.5	2.03	478	829	392	4.06	740	4413
	LowRuminants			355	70.37	82.4	2.15	263	146	2.5	1.96	470	811	395	4.06	739	4505
	HighVegFruitsNuts			331	69.66	81.73	2.14	306	158	8.6	2.04	625	869	546	4.06	736	5471
	HalfOverweight	640	730	327	69.96	82.04	2.1	296	138	8	2.04	557	847	450	4.06	724	4939
	NoUnderweight	0	1461	224	69.76	81.84	2.08	305	153	8.6	2.04	588	855	471	4.06	733	5164
	LowFoodWaste			364	70.03	82.2	2.13	286	134	7.3	2.03	520	838	425	4.06	708	4673
Livelihoods	**Livelihoods**				70.06	82.32	2.12	299	140	7.6	2.03	702	856	397	7.08	730	5019
	LibTrade				69.95	82.2	2.13	298	146	7.6	2.03	556	834	435	4.06	729	4978
	MinWage				69.95	82.03	2.1	303	148	8.2	2.04	712	862	426	7.08	730	5067
	CapitalSubst				69.87	81.86	2.07	303	144	8.5	2.04	587	852	485	4.06	731	5206
Biosphere	**Biosphere**				70.44	84.02	2.07	306	0	5	2.01	621	879	460	4.06	730	5251
	REDD+				70.17	82.96	2.06	305	157	5.1	2.01	610	874	460	4.06	730	5153
	LandConservation				69.75	82.88	2.08	303	165	8.3	2.04	588	854	461	4.06	730	5099
	PeatlandRewetting				69.61	81.82	2.08	304	158	7.1	2.03	584	853	460	4.06	730	5114
	WaterConservation				69.72	81.86	2.09	302	0	8.8	2.04	575	851	461	4.06	730	5100
	BiodivOffset				70.43	82.86	2.09	305	150	7.6	2.03	589	861	461	4.06	730	5098
Agriculture	**Agriculture**				70.54	82.53	2.14	217	336	1.7	1.96	716	905	669	4.06	731	6170
	NitrogenEfficiency				69.77	81.66	2.1	217	144	7.6	2.03	604	859	515	4.06	731	5329
	CropRotations				69.24	81.21	2.28	302	214	9.5	2.05	578	853	463	4.06	732	5159
	LandscapeHabitats				70.47	81.79	2.09	303	143	8.4	2.04	580	851	461	4.06	730	5091
	RiceMitigation				69.84	82.13	2.09	303	146	8.2	2.03	577	851	470	4.06	730	5119
	LivestockManagement				69.68	81.74	2	306	169	6	2	648	877	581	4.06	730	5710
	ManureManagement				69.83	81.77	2.09	297	145	7.9	2.03	591	855	484	4.06	732	5206
	SoilCarbon				69.67	82.91	2.06	304	169	5.5	2.02	584	856	461	4.06	730	5129
	FST_SSP2	0	730	144	70.9	84.9	2.46	171	0	-5.6	1.86	539	835	385	7.08	718	4011
CrossSector	**CrossSector**	530	1610	238	69.7	81.52	2.07	274	172	7.1	1.74	549	242	346	5.71	1065	5555
	Population	606	1446	407	69.87	82.15	2.12	294	142	7.3		582	854	431	4.06	719	4883
	HumanDevelop	556	1633	215	69.62	81.74	2.16	270	142	9		544	241	318	5.71	716	4975
	EnergyTrans				69.85	81.65	2.01	326	166	9	1.73	574	849	528	4.06	988	5786
	Bioplastics				69.79	81.82	2.08	307	153	8.6		576	850	472	4.06	782	5195
	TimberCities				69.8	81.86	2.09	303	148	7.7		582	853	461	4.06	794	5213
	FST_SDP	0	805	103	71.06	84.81	2.35	166	0	-6.7	1.53	452	225	304	7.81	1059	4649

Figure 2

The impact of Food System Measures(FSMs) on key outcome indicators. Green fields indicate an improvement compared to the reference BASE$_{SSP2}$ in 2050, red colors indicate a deterioration compared to the reference. Gray fields have not been quantified (see footnotes and SI table). The Food System Transformation (FST) scenarios combine the packages Diets, Livelihoods, Biosphere and Agriculture, once in the context of the SSP2 scenario (FST$_{SSP2}$), and once in the context of a Sustainable Development Pathway (FST$_{SDP}$), which includes CrossSector impacts from measures outside the food system. All indicators refer to the state in the year 2050. A description of FSMs and outcome indicator can be found in Extended Data Table 1 and 2.

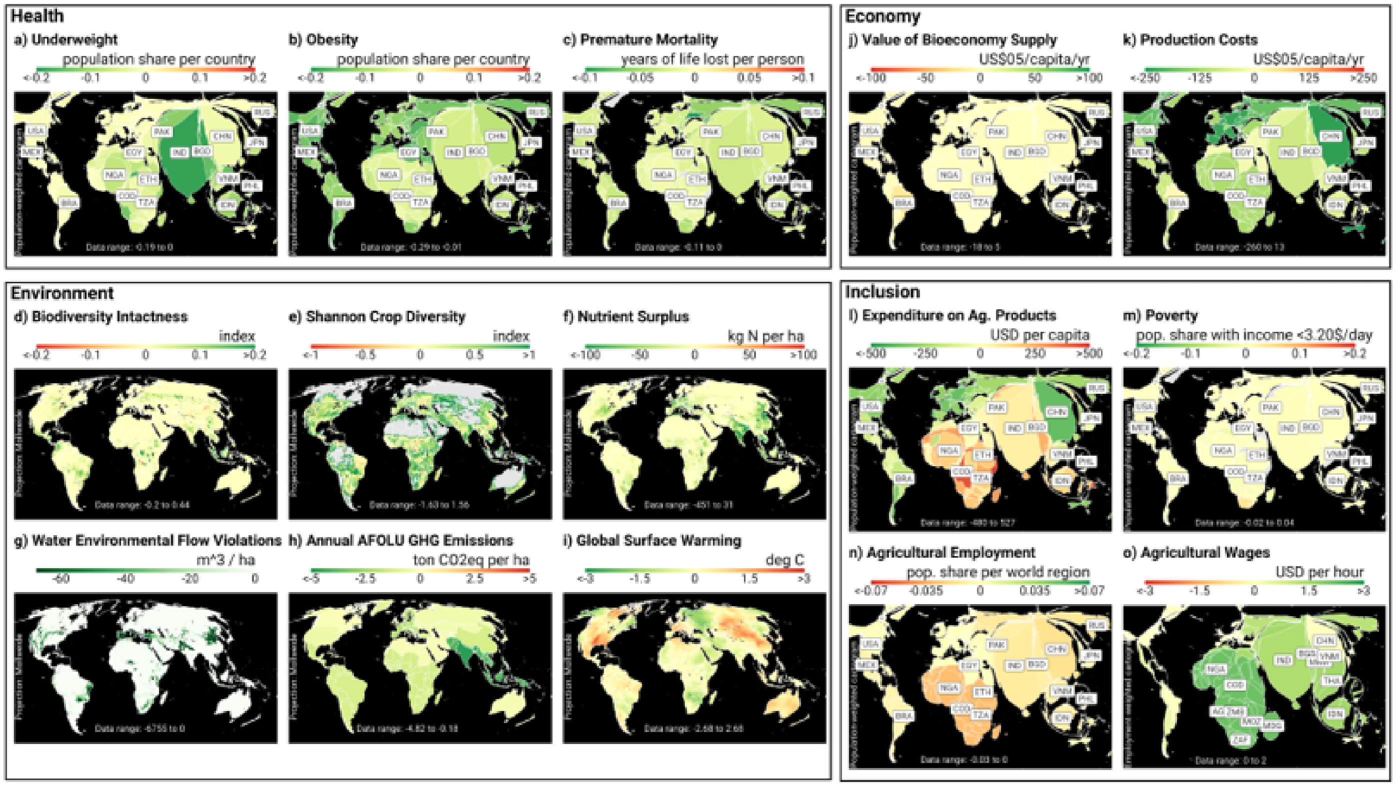

Figure 3

A sustainable development pathway with a food system transformation could achieve large food system co-benefits (green) for health, environment, inclusion and the economy, yet geographical patterns differ, and some trade-offs (red) occur, most importantly with respect to employment and costs. The maps depict the difference of the 15 food system outcome indicators between the $\mathrm{FST}_{\mathrm{SDP}}$ scenario and the reference scenario $\mathrm{BASE}_{\mathrm{SSP2}}$. Spatial resolution differs by indicator (Extended Data Table 2), and we use a Mollweide projection (area-preserving projection, per-ha values are per total cell area) for environmental indicators, and a Cartogram projection (areas proportional to population or agricultural workers) for health, inclusion and economy indicators.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Supplement.xlsx
- HealthassessmentSImethods011923.docx
- SupplementaryInformation.docx
- Extendeddata.docx