Bundled measures for China's food system transformation reveal social and environmental co-benefits

Xiaoxi Wang[1,2,3*], Hao Cai[1,2], Jiaqi Xuan[1,2], Ruiying Du[1,2], Bin Lin[1,2], Benjamin Leon Bodirsky[3], Miodrag Stevanović[3], Quitterie Collignon[3], Changzheng Yuan[4,5], Lu Yu[6,7], Michael Crawford[3], Felicitas Beier[3,12], Meng Xu[1,2], Hui Chen[4], Marco Springmann[9,10], Debbora Leip[3,11], David Meng-Chuen Chen[3,11], Florian Humpenöder[3], Patrick von Jeetze[3,11], Shenggen Fan[8], Bjoern Soergel[3], Jan Philipp Dietrich[3], Christoph Müller[3,1], Alexander Popp[3,12], Hermann Lotze-Campen[3,1,13*]

[1]China Academy for Rural Development, School of Public Affairs, Zhejiang University, China

[2]MAgPIE-China research group, China

[3]Potsdam Institute for Climate Impact Research, Member of the Leibniz Association, Germany

[4]School of Public Health, the Children's Hospital, and National Clinical Research Center for Child Health, Zhejiang University School of Medicine, China

[5]Department of Nutrition, Harvard T.H. Chan School of Public Health, USA

[6]Department of Land Management, School of Public Affairs, Zhejiang University, China

[7]German Institute of Development and Sustainability, Germany

[8]China Agricultural University, China

[9]Oxford University, UK

[10]London School of Hygiene & Tropical Medicine, UK

[11]IRI THESys, Humboldt-Universität zu Berlin, Germany

[12]Faculty of Organic Agricultural Sciences, University of Kassel, Germany

[13]Department of Agricultural Economics, Humboldt-Universität zu Berlin, Germany

*Corresponding authors. Email: xiaoxi_wang@zju.edu.cn; lotze-campen@pik-potsdam.de

Abstract

Food systems are essential for the achievement of the UN Sustainable Development Goals in China. Using an integrated assessment modeling framework that considers country-driven pathways and covers 18 indicators, we find that most social and environmental targets for the Chinese food system under current trends are not aligned with the UN Agenda 2030. We further quantify the impacts of multiple measures, revealing potential trade-offs in pursuing strategies aimed at public health, environmental sustainability, and livelihood improvement in isolation. Among the individual packages of measures, a shift towards healthy diets exhibits the lowest level of trade-offs, leading to improvements in nutrition, health, environment and livelihoods. In contrast, focusing efforts on climate change mitigation and ecological conservation, or promoting faster socio-economic development alone, have trade-offs between social and environmental outcomes. These trade-offs could be minimized by bundling all three aspects of measures.

Main

China's unprecedented economic growth over the past decades has lifted millions of people out of poverty and hunger while reshaping its food system[1]. The rapid change of the country's food system poses pressing challenges to public health, the environment, and livelihoods[1–3]. Overall dietary quality remains suboptimal, responsible for 51% of all cardiometabolic deaths and 21% of total deaths between 2010 and 2012[4]. Environmentally, with increasing concern about the overuse of nitrogen (N) fertilizer, the country's efforts are particularly devoted to enhancing N use efficiency (NUE)[2]. Food systems and the economy are closely interlinked[1,5]. Malnutrition results in substantial economic losses at the individual and societal levels. Individuals are estimated to suffer productivity losses amounting to over 10% of their lifetime earnings, while the gross domestic product (GDP) lost to malnutrition can range from 2% to 3%[6]. The inefficient food system creates 19% of food losses[7], suggesting that 4%–5% of China's workforce work in vain[8,9].

The global development agenda recognizes the imperative of comprehensively transforming the food system for sustainable development[10–13], and policymakers in China acknowledge this necessity[1,2]. Achieving a sustainable food system transformation, framed as green agriculture with high-quality development in the Chinese context, requires high standards not only for sustainable agricultural production but also in terms of food consumption and public health[1,5]. However, the feasibility of achieving future targets for the Chinese food system is yet understood, and trade-offs and co-benefits need to be unveiled[14]. The existing studies often neglect socioeconomic and biophysical dynamics on which the food system hinges and focus on selective policy measures, such as nutrient management[3] and dietary changes[4].

Here, we examine potential pathways for the sustainable development of the Chinese food system. Our systematic approach aligns with a global sustainable food system transformation[15,16] to assess the combined health, environmental, and socioeconomic dynamics under multiple future scenarios of the Chinese food system (Table 1).

We begin the assessment with a baseline scenario ($BASE_{SSP2}$) that is constructed from the middle-of-the-road Shared Socioeconomic Pathway SSP2[17,18] and incorporates the Chinese food system *status quo*. We then consider three package scenarios that correspond to three respective sets of sustainable transformation measures of the food system based on China-specific data and conditions (Extended Data Fig. 1 and Extended Data Table 1). Set A (*Diets* scenario) entails transitioning towards dietary recommendations of the EAT-Lancet Commission[12], while incorporating Eastern healthy dietary patterns proposed by the Chinese Dietary Guidelines (CDG)[19] for China, along with targets to reduce food waste, overcome undernutrition and halve overnutrition by 2050. These ambitious targets align with recent developments in China, including updates of CDG and the release of the Healthy China 2030 Plan[20], which emphasize responsible and healthy diets to promote public and planetary health. Set B (*SustEnvironment* scenario) prioritizes sustainable agriculture management and land use, along with strengthened ecological conservation and climate change mitigation. This aligns with China's environmental protection goals for soil[21], air[22], and water[23]. China's recent pledge for climate neutrality by 2060 underscores its commitment to reduce greenhouse gas (GHG) emissions[1]. Biodiversity conservation and regeneration are also high priorities, exemplified by CBD COP 15[24]. Set C (*Livelihoods* scenario) prioritizes socioeconomic progress and lifestyle transformation within and beyond the food system, aiming for livelihood improvement. This is a key objective of the food system transformation, acknowledging the challenges faced by the impoverished producers and consumers who are the most economically vulnerable groups in society since their livelihoods heavily depend on agriculture and are often influenced by social and environmental factors[15,25–29]. We further integrate all measures from sets A-C into a combined scenario, that is, the Chinese food system transformation pathway (FST_{SDP_China}) to reveal the impacts and the interactions of sets A–C.

This study builds on an analysis of a global food system transformation pathway[16] that employs the same benchmark methodology and integrated assessment framework (details in Methods). This ensures that the transformation pathway of the Chinese food system aligns with sustainable development objectives on the global scale while taking into account country-driven multi-objective pathways[30,31]. The core of this integrated modeling framework is MAgPIE-China (a China version of Model of Agricultural Production and its Impact on the Environment)[2,32–35], linked with several sectoral models to cover health and livelihood aspects[13,25]. MAgPIE-China is an agro-economic land system model designed to minimize costs while satisfying the demand for agricultural products. Key assumptions of this modeling analysis include that income drives food waste and productivity increase drives reduction in labor requirement. More details about the assumptions can be found in Extended Data Table 1 and Supplementary Information. We analyze model results from 2020 to 2050 and combine a validation phase from 1995 to 2015 for model quality checks. In addition to health and environmental indicators, we incorporate the aspect of livelihoods to broaden our understanding of the impacts related to social progress, which is measured in terms of agricultural expenditure, population in poverty, agricultural employment, agricultural wage, bioeconomy supply, and production costs.

Our study quantifies the social and environmental impacts of the Chinese food system in five scenarios (Table 1). For each scenario, we estimate the outcomes in terms of 18 indicators, highlighting domains requiring urgent changes. These 18 outcome indicators are selected from a condensed Sustainable Development Goals (SDGs) target space[1,15,16,36] that are intrinsically related to social and environmental impacts of food system transformation (Supplementary Table 1) and belong to three categories: 1) scenario targets, 2) endogenous outcomes from the modeling framework, and 3) results from downstream models. A comprehensive (though incomplete) set of indicators aligned with the SDGs[16,36] is developed to monitor progress in the Chinese food system. We examine the joint impacts of multiple measures, revealing potential trade-offs in pursuing strategies aimed at public health, environmental sustainability, and livelihoods in isolation during the transformation of the Chinese food system. Promoting a comprehensive food system transformation can maximize co-benefits and minimize trade-offs. This sheds light on areas needing substantial efforts and coordinated governance and implies the importance of synergizing measures in the Chinese food system transformation for enhanced social and environmental progress.

Results

We first assess the social and environmental impacts of the Chinese food system in the $BASE_{SSP2}$ scenario. Under current trends, we project that China's public health would continually face challenges related to malnutrition. The underweight population will approximately halve to 25 million in 2050 relative to 2020, while the prevalence of obesity will increase to 202 million people (Fig. 1). The double burden of malnutrition[37] is inextricably linked to suboptimal diets, which are among the top five risk factors that are strongly associated with health and longevity[5]. Animal-sourced and empty-calorie foods account for 52% of daily calorie intake in 2050 (Fig. 3a), leading to poorer dietary quality in terms of the Chinese Healthy Eating Index (CHEI) and EAT-Lancet Diet Index (EATDI) relative to 2020 (details in Methods). The projected premature mortality attributed to suboptimal diets in China will fall by 2 million in 2050 compared to 2020, but still amount to 38 million years of life lost (YLLs) annually, equivalent to an economic loss of 966 billion USD_{17ppp} per year and 1.4% of the country's projected GDP in 2050 (details in Supplementary Information).

The food system is projected to remain a major driver of environmental damage in the $BASE_{SSP2}$ scenario assuming no additional measures are implemented, rendering the UN Agenda 2030 for SDGs and Paris Climate Agreement unachievable even by 2050 (Fig. 1). The projected biodiversity intactness index (BII) for all land types (details in Methods) slightly increases in 2050 by 0.4 points from 73.9 in 2020, even in the absence of specific measures addressing biodiversity issues. However, the biodiversity hotspot areas in Northern China would remain at lower BII levels (Fig. 2a). This is largely due to the afforestation driven by the Nationally Determined Contributions (NDCs) and the reduction in other natural vegetation (Supplementary Fig. 1). Northwest China has even lower crop diversity, measured as Shannon Index (Fig. 2b). Yet, crop diversity is crucial for enhancing agricultural resilience and adaptability in the face of changing environmental conditions. Annual GHG emissions from agriculture, forestry, and other land use (AFOLU) in 2050 would only decrease to 0.7 Gt CO_2eq/yr (Supplementary Fig. 2), indicating that more ambitions are required to meet the climate neutrality target of 1.5 °C. With inefficient fertilizer use and nutrient management, we project a high N surplus of 35 Mt N/yr in 2050, overshooting the country's N planetary boundary of 26 Mt N/yr[2,38] and thus exacerbating air and water pollution[3], particularly in the North China Plain and the Taihu Basin where agricultural production is concentrated (Fig. 2c). The cumulative N-related emissions from 2020 to 2050 would amount to 625 Mt N (Supplementary Fig. 3), of which N_2O emissions constitute 11 Gt CO_2eq. The violation of environmental water flow requirements is projected to further deteriorate to excessive withdrawals of 23 km^3/yr (+44%) in 2050, with water scarcity still prevailing in North China (Fig. 2d).

With increasing labor productivity, agricultural employment is projected to decline by 93 million agricultural workers in 2050 compared to 2020, with 47 million jobs remaining in primary agricultural production (Fig. 1). Daily food waste would further increase to 927 kcal/capita in 2050 due to increasing income (Fig. 3b), amounting to a total food waste of 126 million tons. This is equivalent to 18% of agricultural labor bound to unproductive activities, indicating the large inefficiency of the food system[1]. The population size within the low-income group (i.e., below 3.65 USD_{17PPP}/capita/day) is projected to decrease by 94% between 2020 and 2050 (Fig. 1). Despite this substantial improvement, the remaining poor are particularly vulnerable to external shocks[39–41], highlighting the need for inclusive food system transformation.

Co-benefits of China's sustainable food system transformation

To assess the potential benefits and challenges associated with food system transformation in China, we examine changes in key indicators within the FST_{SDP_China} scenario, compared to the $BASE_{SSP2}$ scenario. The FST_{SDP_China} scenario represents a pathway towards sustainable development of the Chinese food system.

Regarding public health, the sustainable transformation of the Chinese food system is projected to have large benefits in terms of a 76% decrease in premature mortality in 2050 compared to the $BASE_{SSP2}$ scenario, avoiding a 1% loss of the country's 2050 GDP. Based on our exogenous dietary assumption in accordance with the CDG, the intake of animal-based foods is partly substituted by plant-based foods with a high share of nutritious and healthy vegetables and fruits. The daily intake of animal-based foods (including ruminant meat, pork, poultry, eggs, milk, and fish) would be 290 kcal/capita in 2050, a 62% reduction compared with the $BASE_{SSP2}$ scenario. The slightly lower CHEI in 2050 relative to 2020 is mainly attributed to the reduced intake of eggs (Supplementary Fig. 4). While our dietary scenario and CHEI both align with CDG recommendations, there is a distinction between the two in terms of their approach. In our scenario, we have established an upper limit on egg intake, whereas CHEI promotes egg consumption without imposing any upper bound. The per capita daily intake of sugar and alcohol would also decrease by 28% and 75%, respectively (Fig. 3a). In contrast, the intake of plant-based foods with high nutrient density would substantially increase. The intake of pulses and oilseeds including soybeans and nuts will increase to 261 kcal/capita/day in 2050, and the intake of vegetables and fruits will increase to 484 kcal/capita/day (Supplementary Fig. 5). The finding corroborates existing studies about the potential health benefits of adopting healthy plant-based diets[5].

Environmentally, in the FST_{SDP_China} scenario, natural land with high biodiversity intensity is restored, leading to an overall increase in BII to 75.5 in 2050, while the overall crop area diversity remains unimproved compared to the $BASE_{SSP2}$ scenario (Fig. 1). Spatially, there are substantial improvements in BII in Southwest China where biodiversity hotspots are located (Fig. 2a). Crop area diversity in Central and Northeast China would also improve, which are the major areas of grain production (Fig. 2b). In contrast, it would become worse in South China. Land-use change in 2050 compared to the $BASE_{SSP2}$ scenario is featured with decreasing total areas of cropland and pasture by 68 Mha and increasing forest areas of 30 Mha and natural land areas of 37 Mha (Supplementary Fig. 6). The N surplus can be decreased by 46% (16 Mt N/yr) in 2050 compared to the $BASE_{SSP2}$ scenario (Fig. 2c) and be operated well below the country's N planetary boundary[3,38]. Cumulative N-related emissions from 2020 to 2050 can be reduced by 51% compared to the $BASE_{SSP2}$ scenario, of which N_2O emissions decrease by 49% (Supplementary Fig. 3). This is largely due to further NUE improvement via fertilization standards for different regions and crops, promoting high-efficiency fertilizers, and adopting new fertilization methods[2] (Extended Data Fig. 2). The negative annual GHG emissions of 0.6 Gt CO_2eq/yr in 2050 suggest that China can achieve climate neutrality in its AFOLU sector, which is critical for the country's overall climate neutrality target in 2060[1]. The eradication of excessive water withdrawals in 2050 is feasible in the sustainable transformation pathway (Fig. 2d) where stringent water conservation is introduced jointly with a shift towards healthy diets.

For the livelihoods, the food system sustainable transformation in China would lift a large fraction of the population out of the income group below 3.65 USD_{17PPP}/capita/day, by 87% decrease to 1.4 million people compared to the $BASE_{SSP2}$ scenario, of which 0.2 million live below the income level of 2.15 USD_{17PPP}/capita/day. This is largely due to the rapid economic growth in China projected by the sustainable development pathway following SSP1. The income inequality is decreased given that there is a decrease in the ratio of mean over median income (Supplementary Fig. 7). The annual expenditure for agricultural commodities is almost halved to 459 USD/capita in 2050 compared to the $BASE_{SSP2}$ scenario, resulting from increased intake of healthy and nutritious foods that are more affordable.

Overall employment in agricultural production is projected to shrink by 32% compared to the 2050 $BASE_{SSP2}$ scenario (Fig. 1 and Fig. 3c), indicating the enhanced efficiency of the food system and a structural change. The sustainable transformation pathway entails a 64% increase in labor productivity and assumes 36% higher agricultural wages relative to the 2050 $BASE_{SSP2}$ scenario (Supplementary Fig. 8 and Supplementary Fig. 23). The improvement in labor productivity is accompanied by increased use of capital in agricultural production (e.g., in the form of agricultural machinery). The share of capital costs of total production factor costs is 4% higher than $BASE_{SSP2}$ scenario (Supplementary Fig. 9), suggesting a capital-augmenting and labor-saving technological change. The decrease in production of food crops and livestock products, partly due to the dietary shift towards the recommended food intake target, is another major driver for the reduction in agricultural employment (Supplementary Fig. 10). Additionally, a 49% reduction in food waste relative to the 2050 $BASE_{SSP2}$ (Fig. 3b) frees up 5 million people employed in the labor force otherwise bound to unproductive activities (Extended Data Fig. 2 and Supplementary Fig. 10), indicating an improvement in the overall efficiency of the food system and facilitating labor mobility towards more lucrative sectors[1,42]. Along with a transition towards a more sustainable energy system, expansion in bio-energy production from 9 to 581 Mt DM provides 5 million additional jobs (15% of total agricultural employment in 2050 FST_{SDP_China}) relative to the 2050 $BASE_{SSP2}$ scenario (Fig. 3c) to partly offset the jobs lost in crop and livestock production (Extended Data Fig. 2). The proportion of agricultural employment in the total population is expected to decrease by 1.2 percentage points relative to the 2050 $BASE_{SSP2}$ scenario, whereas the share of agricultural employment in rural areas would increase from 11.8% to 12.4% due to high rates of urbanization (Fig. 3d). With an aging population in China, despite a decrease of 11.1 percentage points in the proportion of agricultural employment in rural areas, there will be an additional 13.9 percentage points of agricultural employment over the age of 55 in 2050 relative to 2020 (Fig. 3c).

Trade-offs and co-benefits between public health, the environment, and livelihoods

China's food system transformation pathway (FST_{SDP_China}) generates substantial co-benefits for public health, the environment, and livelihoods. However, policy measures in China are often initiated and implemented by individual sectors and ministries, leading to less coordinated transformations. To understand the effects of these sector-specific measures, we also examine the package scenarios of *Diets*, *SustEnvironment*, and *Livelihoods*. This approach provides evidence of the co-benefits and trade-offs in the absence of fully coordinated transformation pathways (Fig. 4 and Extended Data Fig. 3).

The scenario *Diets* exhibits the highest level of co-benefits in terms of outcomes among the three sets of measures (Extended Data Fig. 3b). Moving towards diets better aligned with the CDG synergistically improves nutrition and health outcomes (Fig. 4c) can reduce poverty (Fig. 4c) and agricultural employment (Fig. 4g), and has positive impacts on the environmental outcomes (Fig. 4b, d). The transition to diets with higher intake of plant-based foods entails GHG emissions reductions within the AFOLU sector (Fig. 4d). Crop area diversity increases compared to the 2050 $BASE_{SSP2}$ scenario (Fig. 4b), in particular for most of China's major grain production areas (Supplementary Fig. 11b). Improving diets leads to a 29% decrease in agricultural employment in 2050 relative to the $BASE_{SSP2}$ scenario (Fig. 4g), as the primary contributor to structural transformation and efficiency enhancement of the food system. With regards to the three individual measures in the *Diets* scenario, the reduction in per capita daily total calorie intake in this scenario results in a 0.9% decline in agricultural employment (Supplementary Fig. 10). The reduction in food waste reduces agricultural employment by 10% while shifting Chinese diets in concert with the dietary guideline contributes to a 19% reduction of agricultural employment. Animal-sourced food consumption (i.e., food intake and waste) will reduce by 64% in 2050 compared to the baseline level, leading to a 58% (15 million) reduction in employment in livestock production and 77% decline in feed production (from 7.2 million to 1.6 million) (Supplementary Fig. 12). Despite the overall downward trend of agricultural employment, it is worth noting that shifting food consumption in accordance with the dietary guideline increases consumption of plant-based foods including vegetables, fruits, pulses, and nuts, which is expected to employ an additional 4.1 million people.

In the *SustEnvironment* scenario, there are substantial environmental benefits but trade-offs with livelihoods. Indicators related to biodiversity are improved since land use is the most dominant direct driver of anthropogenic biodiversity loss and the set of measures leads to targeted restoration of areas with high biodiversity along with a decrease in cropland and pasture areas (Supplementary Fig. 11). The targeted protection of environmental water flow requirements does not have major adverse impacts on the other environment indicators (Extended Data Fig. 3c). The reform of China's fertilizer policies, including the imposition of stringent fertilizer prices and the improvement of NUE, reduces nitrogen pollution and supports the restoration of natural lands and reduction of agricultural water use and N surplus (Supplementary Fig. 11). Our model results indicate that there are slightly negative impacts on livelihoods when improving environmental sustainability (Fig. 4f, h, i). Maintaining the same level of agricultural wage, there would be an increase in both low-income population and agricultural employment compared to the $BASE_{SSP2}$ scenario in 2050. This is largely due to two specific measures, namely, *AgroMitigation* and *NitrogenEfficiency*, which generate higher production costs and expenditure on agricultural products (Extended Data Fig. 2), thus enlarging the agricultural economy. Within the environmental protection domain, crop area diversity (Fig. 4e) is negatively affected, indicating internal trade-offs within the environmental protection domain. This is partly due to the stringent biodiversity and GHG Mitigation measures leading to more intensified crop production which may unintentionally limit crop diversification (Supplementary Fig. 11b).

The *Livelihoods* scenario prioritizes enhancing livelihoods, characterized by higher agricultural wages, increased labor productivity, rapid economic growth, and low population growth. The assumed increase in agricultural wages plays a crucial role in supporting the income growth of agricultural workers. The population in the low-income group below 3.65 USD_{17PPP} per capita per day in China would decrease to 1.4 million people even though agricultural employment faces a sharp decline (Fig. 4i). It is worth noting that the emphasis on social outcomes can have mixed impacts on public health and environmental sustainability. There are both decreases in the underweight population and premature mortality in 2050 (Fig. 4a), while the number of people with obesity is projected to increase to 227 million in 2050 due to the persistence of suboptimal diets along with the growing income, characterized by a high consumption of red meat (Extended Data Fig. 3d). Concerning the environmental outcomes, GHGs emitted in the AFOLU sector would decrease by 354 Mt CO_2eq mainly due to the external energy transition in the context of overall sustainable development (Fig. 4f). However, biodiversity (Fig. 4h), crop area diversity (Fig. 4e), and water scarcity (Fig 1) are expected to further deteriorate relative to the baseline level. The expansion of bioenergy production could lead to more severe water scarcity and a decrease in crop area diversity due to the cultivation of bioenergy crops. To provide materials for the bioplastic and construction industries, there would be a decrease in BII due to the growing timber demand (Extended Data Fig. 2).

Discussion

Our model results underscore that most outcomes in the $BASE_{SSP2}$ scenario, even by 2050, are not aligned with the UN Agenda 2030 for SDGs and the Paris Climate Agreement. Under current trends, the Chinese food system is expected to continuously pose nutrition and health challenges. Specifically, the double burden of malnutrition due to poor dietary quality persists, with diet-related premature mortality amounting to 1.4% of the country's projected GDP in 2050. The environment further degrades, including deteriorating environmental water flows, overshooting the N planetary boundary, and increased GHG emissions. Meanwhile, 18% of the country's agricultural employment is still bound to activities that produce waste and 10.5 million people would live below the income level of 3.65 USD_{17PPP}/capita/day in 2050.

Substantial social and environmental progress in the Chinese food system is contingent on the joint implementation of multiple measures spanning public health, the environment, and livelihoods. Our model results highlight the need for a comprehensive and coordinated approach, such as the food system transformation pathway, to address these interlinked challenges in the Chinese food system. Achieving SDG 2 (Zero Hunger) and SDG 3 (Good Health and Well-being) is feasible by eliminating undernutrition and halving the prevalence of obesity through the shift towards healthier diets in accordance with the recommended dietary guidelines[12,19]. Efforts in climate mitigation and ecological conservation not only improve overall biodiversity and critical ecosystem services but also contribute to net zero GHG emissions in the AFOLU sector, resonating with SDG 6 (Clean Water and Sanitation), SDG 13 (Climate Action) and SDG 15 (Life on Land). Progress in socioeconomic development and lifestyle transformations acts as catalysts for income growth and employment restructuring, which are closely associated with SDG 1 (No Poverty), SDG 8 (Decent Work and Economic Growth), and SDG 10 (Reduced Inequalities).

Reconciling trade-offs in China's food system transformation

Trade-offs and co-benefits arise in the proposed food system transformation in China. For instance, stringent biodiversity and GHG mitigation efforts in the *SustEnvironment* scenario may unintentionally reduce crop diversification and exacerbate poverty, impacting low-income populations who rely on diverse crops for dietary quality[44] (Extended Data Fig. 2). In the *Livelihoods* scenario, measures for energy transition and capital substitution may adversely affect crop area diversity and the adherence to regional nitrogen surplus boundaries (Extended Data Fig. 2). The *Diets* Scenario emphasizing changing food consumption is found to be the most synergistic among the three package scenarios (Extended Data Fig. 3). Particularly, adhering to the recommended dietary guidelines is a crucial lever for transforming the Chinese food system towards sustainability[1,12,13,31]. In line with the existing studies on dietary transformation[13,15], dietary shift has the potential to generate substantial positive impacts on multiple indicators related to the sustainability of the food system, such as reducing GHG emissions, improving public health outcomes, and preserving natural land and water resources.

Addressing negative impacts requires a combination of measures that reconcile trade-offs across public health, the environment, and livelihoods. Our model results indicate that the integration of these three package scenarios shows large improvements across all indicators, confirming the effectiveness of coordinated policy approaches. The agricultural sector faces a decline, with employment projected to decrease to 2.4% of the total population by 2050, similar to trends in the United States (0.8%) and Japan (1.7%) in 2020[45]. An aging agricultural workforce with 51% of its workforce over the age of 55 by 2050, yet younger than Japan's current average age of 66.8 years[46].

The exit of smallholder farmers can facilitate land consolidation and agricultural mechanization, supporting our expectations of continued growth in agricultural wages and labor productivity. However, additional policy measures are necessary to support both the sector and farmers. Agriculture support in terms of subsidies in China increased from 9.5% of production value in 2000–2002 to 17.6% in 2019–2021[46], but distortions due to subsidies suggest a need for reallocation towards infrastructure investment, research on nutritious and sustainable food alternatives[47], and safety nets for vulnerable groups in rural areas[34,48]. The EU Common Agricultural Policy serves as a model for smoothing transitions, emphasizing direct payments, investments in research and development, training for unskilled labor, and rural development[46].

Potential new employment opportunities are emerging in other sectors such as bioenergy production. Bioenergy with Carbon Capture and Storage (BECCS) could offset part of the negative impacts of the food system transition on employment and also contribute to GHG emissions reduction[49]. Moreover, broadening the scope has the potential to transform the nutrition and health industry into a powerful driver of both health improvement and livelihoods. This holistic approach considers not only the health outcomes but also the environmental and livelihood issues, creating new employment opportunities across various sectors, including caregiving, nursing, medical services, and food and nutrition education[1].

A guiding pathway to support evidence-based policymaking

This study provides a detailed analysis of potential measures for transforming the Chinese food system and identifies domains where urgent changes are needed. By doing so, we offer model-based insights on where significant efforts should be devoted, where coordinated governance is required, and which combined measures are needed. A sustainable food system can only be reached through coordinated governance because of the wide range of social and environmental problems connected to the food system. The food system needs diverse and varied policy instruments due to its greater complexity compared to the energy system, and a single measure like GHG pricing alone is insufficient[1]. Our findings support the establishment of a monitoring framework to inform future actions and policies for the Chinese food system transformation towards achieving the UN Agenda 2030[16,42].

Changing dietary behaviors is essential yet challenging, requiring large shifts in individual and societal practices[1,50]. Educational programs, information provision[51,52], and behavioral nudges can raise awareness of food choices[53], while regulations or taxation can provide economic incentives to promote sustainable food choices[54]. In the distinct context of Chinese food culture, refining the national dietary guidelines to incorporate the Eastern healthy dietary pattern[19], the planetary health diet[12], and elements of Chinese cuisine specialty can help navigate the food system transformation. Technological innovations in cold-chain logistics, high-barrier packaging, and blockchain can further reduce food loss and waste, enhancing food safety and quality[55]. Financial support, income transfers, and investments in infrastructure and technological innovation are crucial for the adoption of green technologies and the enhancement of human capital. These efforts not only contribute to productivity growth and sustainable agriculture but can alleviate poverty[15,25].

Policy measures are under the responsibility of various governmental branches and their success can hinge on coordination with other measures. While understanding individual measures is crucial for implementing transformation pathways, coordinating policies to balance sustainability aspects is equally important. A coordinated governance system is necessary to align policies for co-benefits and minimize trade-offs, which is particularly challenging in China's sector-specific policy environment. A rigorous, science-based monitoring framework can facilitate evidence-based policymaking and hold key actors accountable during the transformation process[1,42]. Moreover, the country's localized initiatives can have a substantial impact on the global food system through the international market. By adopting eco-labeling and certification schemes, China can foster environmentally friendly practices among its trade partners[56]. As a major importer of agricultural products, the monitoring framework of China's food system transformation can better facilitate global food system transformation.

Several caveats should be considered when interpreting our results. While we cover a broad range of indicators, it addresses a subset of the potential social and environmental impacts of China's food system transformation. Future research should aim to include a more comprehensive representation of SDG indicators. Employing a globally consistent poverty model, we analyze poverty and inequality at the country level, but future research can incorporate more national datasets for a deeper understanding. We recognize the need to consider uncertainty in model results. This study extends the assessment scope by including livelihoods, in addition to health and environmental impacts, which increases the complexity of conducting a systematic sensitivity analysis. Therefore, we conduct a sensitivity analysis based on different combinations of socioeconomic and climate change pathways, and different poverty lines, detailed in the Supplementary Information. A comprehensive uncertainty analysis, while beyond the scope of this study, can be considered for future research.

Methods

MAgPIE-China

The cornerstone of this analysis relies on the MAgPIE (Model of Agricultural Production and its impact on the Environment) partial equilibrium model[32], which is an agro-economic land system model designed to minimize costs while satisfying the demand for agricultural products. The model is developed to describe the land and food sectors and assess the associated consequences for sustainable development under different future scenarios. A more detailed description of the MAgPIE model can be found in the Supplementary Information. To facilitate the study of China's food system transformation pathways, we further develop a China-specific version of the MAgPIE land system modeling framework (MAgPIE-China) to incorporate China-specific data and conditions. Taking into account China's fertilizer policy reform, we estimate the changes in N fertilizer price and the efficiency of agricultural nutrient management induced by the reform and introduce them into the MAgPIE model[2]. For specific water protection measures in China, we set an upper limit on agricultural freshwater use. Further, we calibrate China's agricultural irrigation efficiency using Chinese official data (0.536 in 2015, 0.565 in 2020) and targets (0.58 for 2025, 0.6 for 2035)[35]. We also consider the policy of maintaining minimum cropland[34] in the model with a threshold of 120 million hectares. These China-specific measures are applied across all scenarios in this study. The model runs in a dynamic recursive manner from 2020 to 2050 with a five-year interval. This study uses a mapping of 16 world regions and 200 simulation units (Supplementary Fig. 13) according to their geo-economic conditions. The regional environmental outcomes are further disaggregated to 0.5-degree resolution.

In accordance with the food system modeling framework applied in the analysis of a global food system transformation pathway[16], MAgPIE-China is linked to several models to cover health, environmental, and livelihoods outcomes. The food intake and food waste are estimated based on a food demand model, driven by demographic composition of the population, physical activity level, body height distribution, and income[47]. Dietary composition shifts are projected for four major food categories: animal-sourced foods (including ruminant meat, pork, poultry, eggs, milk, and fish); empty-calorie foods (including oils, sugar, and alcoholic beverages); vegetables, fruits, and nuts; and staple foods. The four groups are then further divided into 25 food items based on the relative share of individual food products within major food groups. The biophysical information including crop yields, water requirements, carbon stocks, and water availability are input from a vegetation, crop, and hydrology model LPJmL (Lund-Potsdam-Jena model with managed Land)[57]. The terrestrial biodiversity is assessed using BII[58,59], which measures net changes of organism abundance based on the loss of forest, non-forest vegetation, and age-class vegetation. A poverty model[25] is run as a post-processing of the MAgPIE-China model results. The macro-economy and energy model REMIND[60] provides bioenergy demands and GHGs prices. Furthermore, the food demand model is linked with a health model to estimate the health impacts of dietary transition[61].

Health model

We employ a comparative risk assessment (CRA) method[61], which links changes in risk factors such as high consumption of red meat, reduced consumption of fruits and vegetables, being underweight, and overweight to changes in cause-specific mortality. The endpoint diseases considered in this study include coronary heart disease (CHD), stroke, type-2 diabetes mellitus

(T2DM), cancer (in aggregate and as colon and rectum cancers), and respiratory disease. The baseline body weight distribution and the corresponding energy intake are projected based on a regression model using country, sex, and age-specific anthropometric data[47]. The relative risk estimates are adopted from a meta-analysis of prospective cohort studies[62–66]. The age-specific mortality and population data are adopted from the Global Burden of Disease project[62].

Two dietary indices, the Chinese Healthy Eating Index (CHEI) and the EAT-Lancet Diet Index (EATDI) are calculated to understand the overall dietary quality across scenarios. The CHEI is developed based on the CDG and Chinese dietary habits[67,68]. In China, the intake of 12 food groups (total grains, whole grain, mixed beans, tubers, total vegetables, dark vegetables, fruits, dairy, soybean, fish and seafood, poultry, eggs, seeds, and nuts) should be increased, while the intake of five food groups (red meat, cooking oils, sodium, added sugar, and alcohol) should be decreased to reach a moderate level. Higher scores on the CHEI indicate better adherence to the CDG. As the MAgPIE-China model does not consider whole grain, mixed beans, and sodium, these groups are excluded from our calculation. A detailed scoring standard of the CHEI can be found in Yuan *et al.*[67]. The EATDI is a metric for gauging how closely people adhere to the EAT-Lancet diet[69]. The index consists of 14 food groups, including seven emphasized food groups (vegetables, fruits, unsaturated oils and palm oil, legumes, nuts, whole grains, and fish) and seven limited groups (beef and lamb, pork, poultry, eggs, dairy, potatoes, and added sugar). Each food group is given a score of 0-3, and a higher score indicates higher adherence to the intake target. Since the index is based on an energy intake of 2500 kcal/capita/day, we rescale the intake of each group according to total calories across scenarios when calculating the EATDI.

Poverty model

To project the income distribution, we apply an inequality and poverty post-processing model built originally for global REMIND-MAgPIE scenarios[25] to the MAgPIE-China scenarios. Starting from scenarios of the Gini coefficient for the Shared Socioeconomic Pathways (SSPs)[70], we account for food expenditure changes due to food system measure implementations by calculating their impacts on real incomes and inequality levels. Future poverty headcounts under different poverty lines are estimated using the new average income and Gini coefficients, with a regression model fit to recent World Bank poverty and inequality data of around 130 countries. We notice that this globally calibrated model may underestimate the pace of poverty reduction in China in recent years (i.e., reporting higher poverty headcounts than the latest historical data). An exact comparison is complicated by the effects of the COVID-19 pandemic. We also implement a redistribution of tax revenue to the population in scenarios with CO_2 taxes, where the increased production costs lead to higher expenditure on agricultural products and lower real income. Further, a redistribution without changing the level of inequality to the entire population is assumed in the *MinWage* scenario as we cannot specify the agricultural income and income from other sources in our data[16].

Scenario design

We explore the sustainable development pathways of the Chinese food system by adopting a systematic approach aligned with a global sustainable food system transformation while explicitly considering impacts with regard to public health, the environment, and livelihoods[15,16]. Additionally, we consider three sets of food system measures representing distinct transformation pathways that prioritize public health, the environment, and livelihoods, respectively, to understand the co-benefits and trade-offs among proposed indicators. Based on the policy background of China, we implement specific measures on diet, nitrogen, water, and cropland management for China, while the rest of the world still follows general settings in each scenario that is in accordance with the global study[15,16].

$BASE_{SSP2}$

The $BASE_{SSP2}$ scenario is the baseline for our study. We use the Shared Socioeconomic Pathway (SSP) projections for regional development of GDP, population, physical activity level, etc. The $BASE_{SSP2}$ scenario follows the *middle-of-the road* (SSP2) path which projects no significant shift from historical patterns. Meanwhile, climate change impacts are taken into account in the projections of yields, water demand and availability, carbon, and land dynamics. To reflect regional efforts on combating climate change, the NDCs are adopted for future afforestation. Food demand and waste are modelled endogenously, driven by socioeconomic factors and demographic trends derived from historical data, calibrated to align with regional food demand reported in FAOSTAT[71]. All mapped regions follow these settings in this baseline scenario.

Food System Transformation in the Context of a Sustainable Development Pathway in China (FST_{SDP_China})

The FST_{SDP_China} scenario incorporates targeted efforts in China to promote healthy diets, improve nitrogen management, and enhance water management, alongside global actions for a comprehensive transformation of the sustainable food system (FST_{SDP})[16]. For diets and food demand, divergent from the baseline level determined endogenously in $BASE_{SSP2}$, this scenario follows a convergent transition from 2020 to 2050, aligning with the dietary intake targets exogenously set in accordance with the CDG[19]. With respect to nitrogen, we first employ a difference-in-differences (DID) econometric method and country-representative household-level survey data in China to estimate the effects of the policy of "Zero Growth in Synthetic Fertilizer Use" on fertilizer use and yields. We then incorporate the changes in nitrogen inputs and outputs into the nitrogen budget to estimate the changes in soil nitrogen uptake efficiency (SNUpE), which is used as a parameter for the improvement of agricultural nutrient management efficiency in the model. Detailed information about the parametrization of SNUpE is documented in Wang *et al*.[2].

For the whole world, a comprehensive food system transformation scheme is adopted from Bodirsky *et al.*[16]. The food system transformation aims at global sustainable development and simultaneously implements policy measures concerning healthy diet, environment protection, and livelihood improvement. While China gradually follows the CDG, we assume the dietary structure of countries and regions except China's transition towards diets proposed by the EAT-Lancet Commission[12]. Compared with the baseline scenario, a food waste target is proposed which begins in 2020 and achieves in 2050 with a linear convergence speed. Further, a no underweight and half overweight target is included for all regions.

The socioeconomic drivers follow the *Sustainability* pathway (SSP1). The trade barriers are reduced and a global wage lower bound is set. Similar to countries with high capital intensity worldwide, the substitution ratio of labor by capital in China is also assumed to be capped. Biomass demand rises due to increased use in bioplastic production, and a greater quantity of wood is utilized as the construction material. Sustainable development in the energy sector also impacts the food system.

Regarding land management, 30% of the global land area will be under protection by 2030, and global afforestation is limited to a maximum of 500 Mha in only tropical area[72]. Simultaneously, the NDC targets (138 Mha of afforestation areas for China by 2030) remain valid at the regional level. Longer crop rotations are incentivized with payments. The non-agricultural water demand follows the SSP1 projection. Regarding GHG pricing, carbon pricing is included with a budget of 900 Gt CO_2eq to disincentivize CO_2 emissions from land-use change, and to incentivize re/afforestation or peatland rewetting. Technical mitigation measures for methane mitigation of respective emission sources are introduced via feedback on abatement costs. For biodiversity, zero reduction of aggregated BII in all biomes of each biogeographic realm in each world region is implemented after 2020.

Three respective sets of food system transformation measures (*Diets*, *SustEnvironment*, and *Livelihoods* scenarios)

Three measure sets, *Diets*, *SustEnvironment*, and *Livelihoods* are singled out from FST_{SDP_China} as individual transformation schemes focusing on fostering improvements in public health, the environment, and livelihoods, respectively (Extended Data Table 1). *Diets* focuses on improving public health by promoting a shift towards sustainable and health-conscious dietary patterns in line with CDG and EAT-Lancet guidelines, while also striving to cut food waste to 20% of food intake levels by 2050. *SustEnvironment* is dedicated to addressing environmental concerns, encompassing measures of emission pricing, preserving land, crop rotation, water conservation, maintaining biodiversity, mitigating agricultural emissions, enhancing nitrogen use efficiency, and protecting landscapes. *Livelihoods* aims to improve livelihoods, incorporating the strategic involvement of national institutions and governance measures including adopting sustainable socioeconomic pathways, supporting liberalized trade, advancing energy transition, providing agricultural materials for bioplastic, and using more wood for construction materials.

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). The release (version 4.6.5) used in this paper can be found via Zenodo (https://doi.org/10.5281/zenodo.7782037). The technical model documentation is available at https://rse.pik-potsdam.de/doc/magpie/4.6.5/). Additional codes and details for all the participating models tailored to China can be provided upon reasonable request. Data analysis was conducted using R (version 4.1.3), GAMS (version 38.3.0), and the libraries of Potsdam Integrated Assessment Modelling (PIAM) (https://github.com/pik-piam).

Acknowledgments

X.W., H.Ca., J.X., R.D., B.L. and M.X. were supported by the National Science Foundation of China (grant no. 72273126 and 72134006). L.Y. acknowledges the funding from the National Science Foundation of China (grant no. 72104213), and the Fundamental Research Funds for the Central Universities. X.W., L.Y., H.Ca., J.X., R.D., B.L. and M.X. acknowledge funding from the National Key Research and Development Program of China (grant no. 2020YFA0608604). X.W., H.Ca., J.X., R.D., B.L., B.L.B., M.St., Q.C., M.C., F.B., M.X., M.Sp., D.L., D.M.-C.C., F.H., P.v.J., B.S., J.P.D., A.P. and H.L.-C. acknowledge support from Food System Economics Commission (G-2009-01682). M.Sp. acknowledges funding from Wellcome Trust (Award number: 225318/Z/22/Z). D.L. acknowledges funding from Hans-Böckler-Stiftung's Doctoral Scholarship. X.W., C.Y., H.Ch., H.Ca., J.X., R.D., B.L. and M.X. acknowledge support from the Fundamental Research Funds for the Central Universities.

Contributions

X.W., B.L.B., M.St. and H.L.-C. conceptualized the study. X.W., H.Ca., J.X., R.D., B.L., B.L.B., M.St., C.Y., M.C., F.B., M.X., H.Ch., M.Sp., D.L., D.M.-C.C., F.H., P.v.J., B.S., J.P.D., C.M., A.P. and H.L.-C. contributed data and devised the methodology. X.W., H.Ca., J.X., R.D., B.L., B.L.B., M.St. and H.L.-C. performed the analysis and interpreted the results. H.Ca., J.X., R.D., M.C. and X.W. produced the visualizations. X.W. and H.L.-C. acquired the funding. X.W., M.St., Q.C. and H.L.-C. managed the project administration. X.W., H.Ca., J.X., R.D., B.L. and L.Y. wrote the original draft. X.W., H.Ca., J.X., R.D., B.L., B.L.B., M.St., C.Y., L.Y., M.C., D.M.-C.C., S.F., B.S., J.P.D., C.M., A.P. and H.L.-C. participated in discussing the results. All authors contributed to reviewing and editing the manuscript.

Corresponding authors

Xiaoxi Wang - xiaoxi_wang@zju.edu.cn

Hermann Lotze-Campen - lotze-campen@pik-potsdam.de

Competing interests

The authors declare no competing interests.

Table 1. Key attributes and assumptions of the scenarios considered in this study.

Scenarios	**Socioeconomic pathway**	**Key attributes**
$BASE_{SSP2}$	SSP2	Current trends following SSP2
Diets	SSP2	A transition towards healthy and nature-positive diets along with reducing food waste
SustEnvironment	SSP2	Strong efforts on climate mitigation and ecological conservation in the AFOLU sector
Livelihoods	SSP2	Faster socio-economic development and progress on sustainable and shared growth
FST_{SDP_China}	SSP1	A holistic food system transformation in the context of a sustainable development pathway in China. Policy measures in three package scenarios are jointly implemented.

Fig. 1. Health, environmental, and livelihood indicators associated with the Chinese food system under the BASE$_{SSP2}$, FST$_{SDP_China}$, and three package scenarios. The color schemes indicate positive (green) and negative (red) impacts on indicators relative to the values in the 2050 BASE$_{SSP2}$ scenario. Grey cells with values indicate that these output indicators are not affected by the policy measures of the respective scenarios.

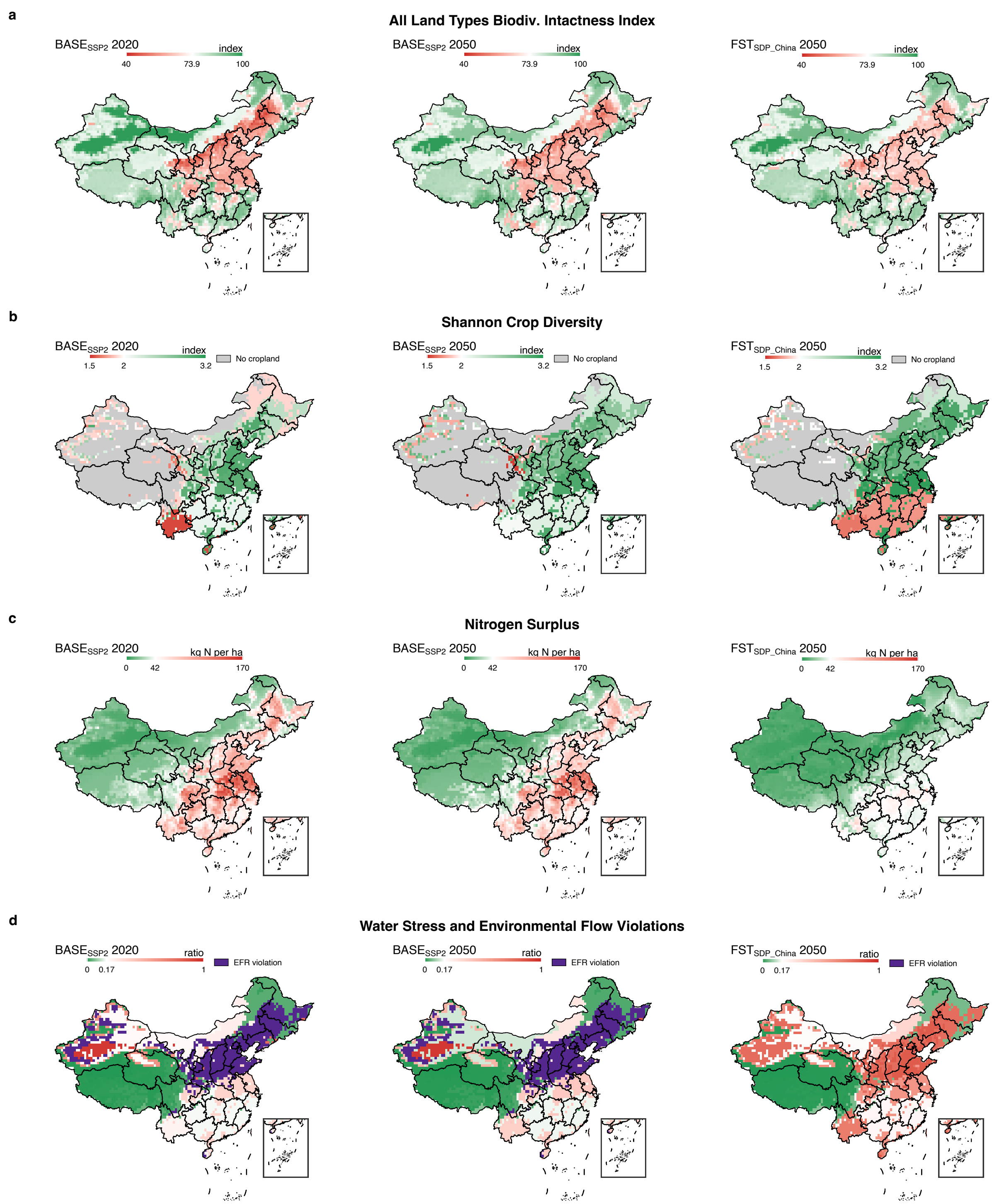

Fig. 2. Spatially explicit environmental indicators in the BASE$_{SSP2}$ scenario for the years 2020 and 2050, and in the FST$_{SDP_China}$ scenario for the year 2050. (**a**) Biodiversity Intactness Index for All Types of Land. (**b**) Shannon Index of Crop Area Diversity. (**c**) Nitrogen Surplus. (**d**) Water Stress and Environmental Water Flow Violations. Green color refers to a better status, while red color refers to a worse status. In panel b, grids without cropland are filled with grey color. In panel d, purple color refers to areas where there are violations of environmental flow requirements. The cut-off numbers for panels in all columns correspond to the average values in 2020 BASE$_{SSP2}$ scenario.

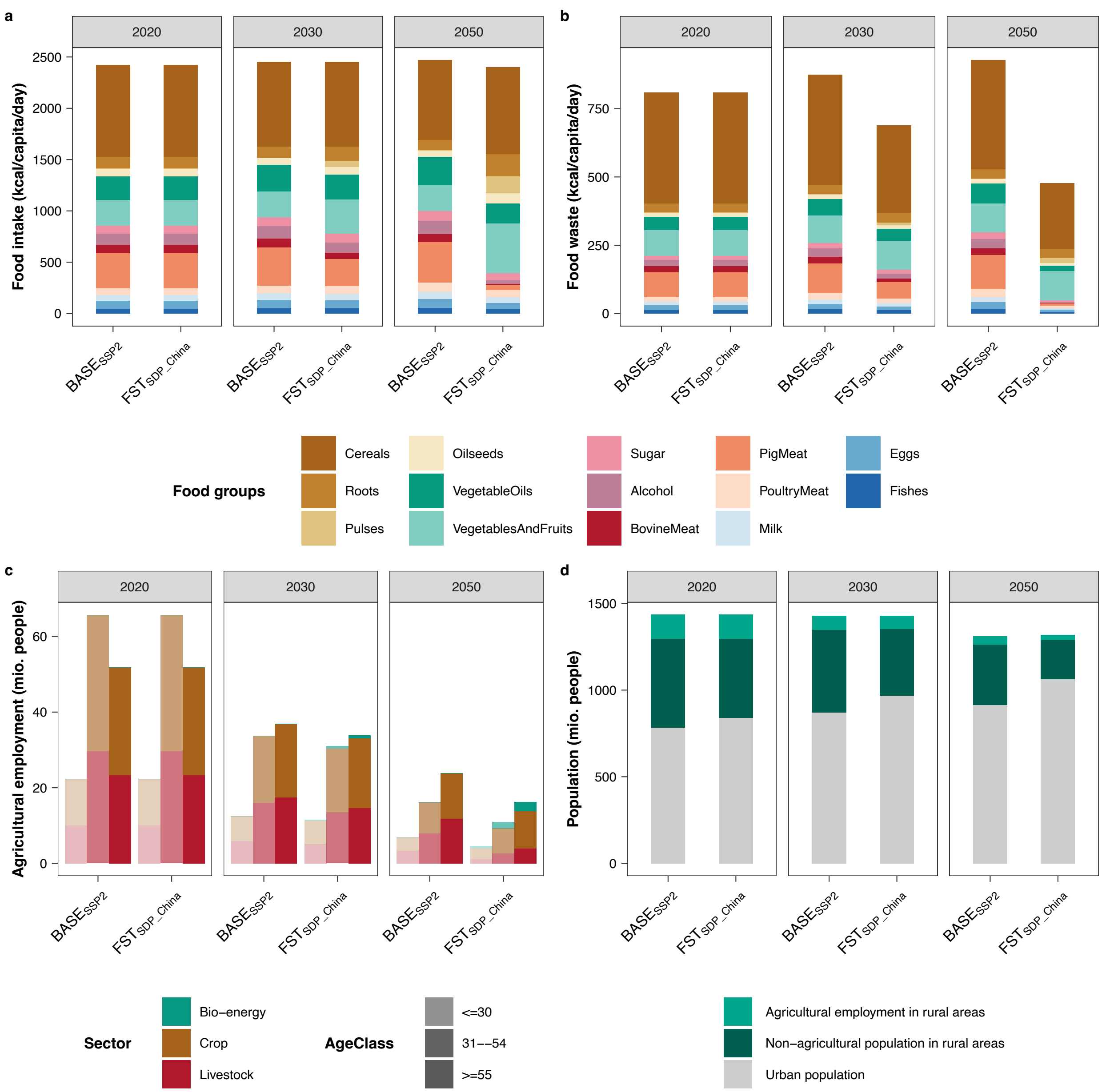

Fig. 3. Dietary patterns and agricultural employment in the BASE$_{SSP2}$ and FST$_{SDP_China}$ scenarios in 2020, 2030, and 2050. (**a**) Intake of specific food groups. (**b**) Amounts of food waste by food groups. (**c**) Agricultural employment in bio-energy, crop, and livestock production across the age classes**.** (**d**) Distribution between urban and rural population and distribution between agricultural employment and non-agricultural population in rural areas**.**

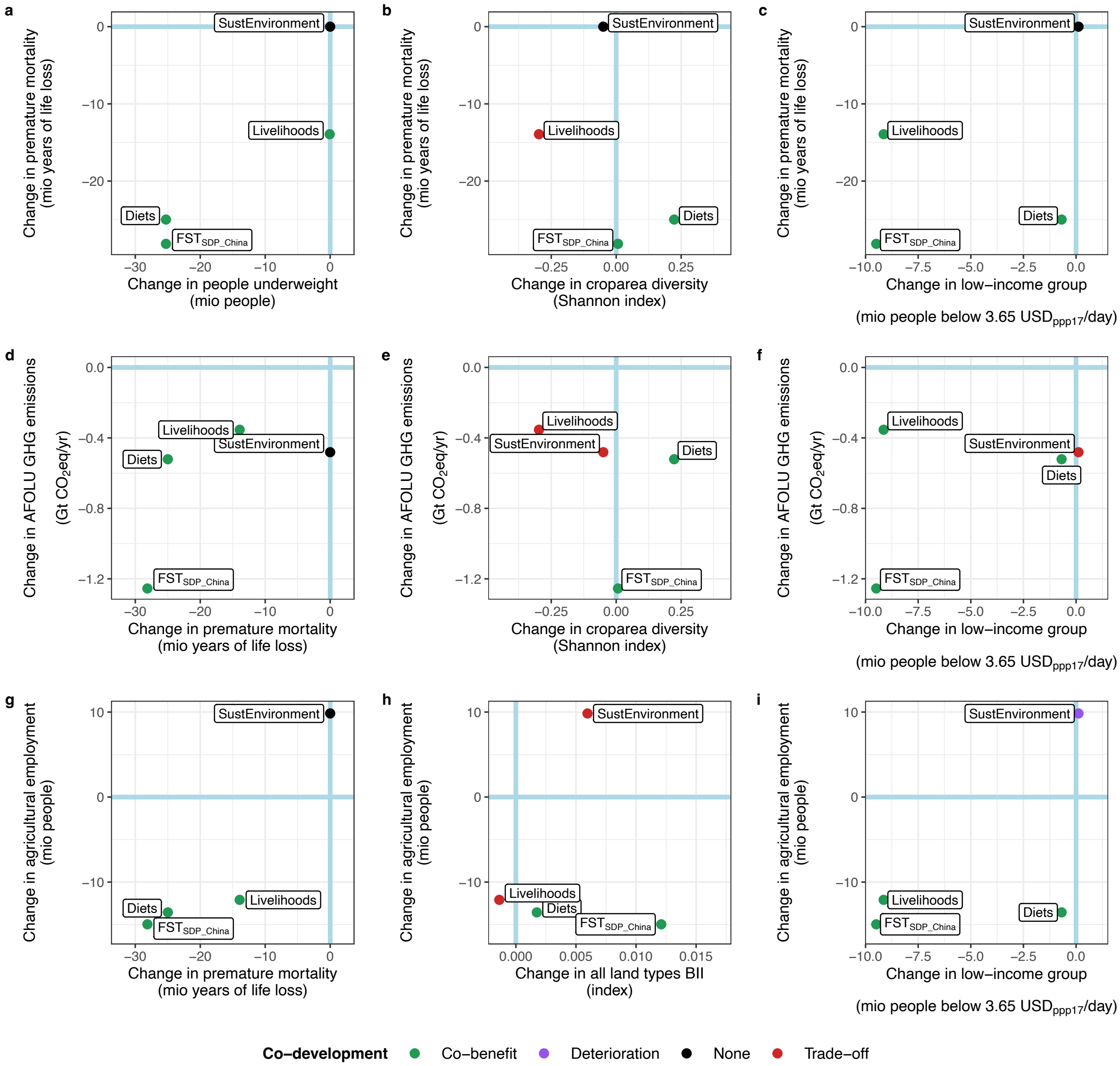

Fig. 4. Co-development of indicators related to public health, the environment, and livelihoods in the Chinese food system. Each panel illustrates the changes in two indicators compared to their baseline levels in 2050. One indicator is plotted on the y-axis (label on the left-hand side) and the other indicator is on the x-axis (label at the bottom). The light-blue vertical line in each panel shows the reference level in 2050 for the x-axis indicator, and the light-blue horizontal line shows the reference level in 2050 for the y-axis indicator. The co-development status of each pair of indicators is represented by the color of the point. A purple point represents both indicators deteriorating together in the respective scenarios. The black color indicates no co-development for the pair of indicators. The green color shows a co-benefit between the two indicators, while the red color refers to a trade

References

1. Wang, X., Bodirsky, B. L., Müller, C., Chen, K. Z. & Yuan, C. The triple benefits of slimming and greening the Chinese food system. *Nat Food* **3**, 686–693 (2022).
2. Wang, X. *et al.* Reforming China's fertilizer policies: implications for nitrogen pollution reduction and food security. *Sustain Sci* **18**, 407–420 (2023).
3. Yu, C. *et al.* Managing nitrogen to restore water quality in China. *Nature* **567**, 516–520 (2019).
4. He, Y. *et al.* The dietary transition and its association with cardiometabolic mortality among Chinese adults, 1982-2012: a cross-sectional population-based study. *Lancet Diabetes Endocrinol* **7**, 540–548 (2019).
5. Chen, H. *et al.* Plant-based dietary patterns in relation to mortality among older adults in China. *Nat Aging* **2**, 224–230 (2022).
6. World Bank. *Repositioning Nutrition as Central to Development: A Strategy for Large Scale Action*. (World Bank, Washington, DC, 2006).
7. Liu, J., Lundqvist, J., Weinberg, J. & Gustafsson, J. Food Losses and Waste in China and Their Implication for Water and Land. *Environ. Sci. Technol.* **47**, 10137–10144 (2013).
8. Gong, P. *et al.* Urbanisation and health in China. *The Lancet* **379**, 843–852 (2012).
9. Zhai, F. *et al.* Dynamics of the Chinese Diet and the Role of Urbanicity, 1991–2011. *Obes Rev* **15**, 16–26 (2014).
10. UNFSS. United Nations. *Action Tracks* https://www.un.org/en/food-systems-summit/action-tracks (2022).
11. Poore, J. & Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science* **360**, 987–992 (2018).
12. Willett, W. *et al.* Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet* **393**, 447–492 (2019).
13. Springmann, M. *et al.* Options for keeping the food system within environmental limits. *Nature* **562**, 519–525 (2018).
14. Breure, T. S. *et al.* A systematic review of the methodology of trade-off analysis in agriculture. *Nat Food* **5**, 211–220 (2024).
15. Soergel, B. *et al.* A sustainable development pathway for climate action within the UN 2030 Agenda. *Nat. Clim. Chang.* **11**, 656–664 (2021).
16. Bodirsky, B. *et al.* A food system transformation can enhance global health, environmental conditions and social inclusion. Preprint at https://doi.org/10.21203/rs.3.rs-2928708/v1 (2023).
17. O'Neill, B. C. *et al.* The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change* **42**, 169–180 (2017).
18. Popp, A. *et al.* Land-use futures in the shared socio-economic pathways. *Global Environmental Change* **42**, 331–345 (2017).
19. Chinese Society of Nutrition. *Chinese Dietary Guidelines*. (People's Medical Publishing House, Beijing, China, 2022).
20. Chen, P., Li, F. & Harmer, P. Healthy China 2030: moving from blueprint to action with a new focus on public health. *The Lancet Public Health* **4**, e447 (2019).
21. The State Council. Notice of the State Council on Printing and Distributing the Action Plan for the Prevention and Control of Soil Pollution. http://www.gov.cn/zhengce/content/2016-05/31/content_5078377.htm (2015).

22. The State Council. Notice of the State Council on Printing and Distributing the Action Plan for the Prevention and Control of Air Pollution. http://www.gov.cn/zwgk/2013-09/12/content_2486773.htm (2013).
23. The State Council. Notice of the State Council on Printing and Distributing the Action Plan for the Prevention and Control of Water Pollution. http://www.gov.cn/zhengce/content/2015-04/16/content_9613.htm (2015).
24. Convention on Biological Diversity. Kunming-Montreal Global Biodiversity Framework. *CBD/COP/15/L25* https://www.cbd.int/conferences/2021-2022/cop-15/documents.
25. Soergel, B. *et al.* Combining ambitious climate policies with efforts to eradicate poverty. *Nat Commun* **12**, 2342 (2021).
26. International Food Policy Research Institute. *2021 Global Food Policy Report: Transforming Food Systems after COVID-19*. https://ebrary.ifpri.org/digital/collection/p15738coll2/id/134343 (2021) doi:10.2499/9780896293991.
27. Wang, X. *et al.* Taking account of governance: Implications for land-use dynamics, food prices, and trade patterns. *Ecological Economics* **122**, 12–24 (2016).
28. Wang, X. *et al.* Beyond land-use intensity: Assessing future global crop productivity growth under different socioeconomic pathways. *Technological Forecasting and Social Change* **160**, 120208 (2020).
29. Evenson, R. E. & Gollin, D. Assessing the Impact of the Green Revolution, 1960 to 2000. *Science* **300**, 758–762 (2003).
30. Jones, S. K., Monjeau, A., Perez-Guzman, K. & Harrison, P. A. Integrated modeling to achieve global goals: lessons from the Food, Agriculture, Biodiversity, Land-use, and Energy (FABLE) initiative. *Sustain Sci* **18**, 323–333 (2023).
31. Mosnier, A. *et al.* How can diverse national food and land-use priorities be reconciled with global sustainability targets? Lessons from the FABLE initiative. *Sustain Sci* **18**, 335–345 (2023).
32. Dietrich, J. P. *et al.* MAgPIE 4 – a modular open-source framework for modeling global land systems. *Geosci. Model Dev.* **12**, 1299–1317 (2019).
33. Lotze-Campen, H. *et al.* Global food demand, productivity growth, and the scarcity of land and water resources: a spatially explicit mathematical programming approach. *Agricultural Economics* (2008) doi:10.1111/j.1574-0862.2008.00336.x.
34. National Development and Reform Commission. Guidelines of the Eleventh Five-Year Plan for National Economic and Social Development. https://www.gov.cn/gongbao/content/2006/content_268766.htm (2006).
35. The State Council. Opinions of Applying the Strictest Water Resources Control System. https://www.gov.cn/zhuanti/2015-06/13/content_2878992.htm (2012).
36. Schneider, K. R. *et al.* The state of food systems worldwide in the countdown to 2030. *Nat Food* **4**, 1090–1110 (2023).
37. Popkin, B. M., Corvalan, C. & Grummer-Strawn, L. M. Dynamics of the double burden of malnutrition and the changing nutrition reality. *The Lancet* **395**, 65–74 (2020).
38. Chang, J. *et al.* Reconciling regional nitrogen boundaries with global food security. *Nat Food* **2**, 700–711 (2021).
39. Stevanović, M. *et al.* The impact of high-end climate change on agricultural welfare. *Science Advances* **2**, e1501452 (2016).

40. Hsiang, S. *et al.* Estimating economic damage from climate change in the United States. *Science* (2017) doi:10.1126/science.aal4369.
41. Hasegawa, T. *et al.* Risk of increased food insecurity under stringent global climate change mitigation policy. *Nature Clim Change* **8**, 699–703 (2018).
42. Fanzo, J. *et al.* Viewpoint: Rigorous monitoring is necessary to guide food system transformation in the countdown to the 2030 global goals. *Food Policy* **104**, 102163 (2021).
43. Jaureguiberry, P. *et al.* The direct drivers of recent global anthropogenic biodiversity loss. *Science Advances* **8**, eabm9982 (2022).
44. Xuan, J., Yuan, C., Jin, S., Tian, X. & Wang, X. Substitute or Complement? Quantity-Quality Effects of Agricultural Production Diversity and Market Access on Dietary Diversity and Nutritional Outcomes in Rural China. (2023).
45. International Labour Organization. ILOSTAT. https://ilostat.ilo.org/data/.
46. OECD. *Agricultural Policy Monitoring and Evaluation 2022: Reforming Agricultural Policies for Climate Change Mitigation*. (OECD, 2022). doi:10.1787/7f4542bf-en.
47. Bodirsky, B. L. *et al.* The ongoing nutrition transition thwarts long-term targets for food security, public health and environmental protection. *Scientific Reports* **10**, 19778 (2020).
48. Gautam, M. *et al. Repurposing Agricultural Policies and Support: Options to Transform Agriculture and Food Systems to Better Serve the Health of People, Economies, and the Planet*. (World Bank, 2022). doi:10.1596/36875.
49. Humpenöder, F. *et al.* Investigating afforestation and bioenergy CCS as climate change mitigation strategies. *Environ. Res. Lett.* **9**, 064029 (2014).
50. Eker, S., Reese, G. & Obersteiner, M. Modelling the drivers of a widespread shift to sustainable diets. *Nat Sustain* **2**, 725–735 (2019).
51. Bauer, J. M., Bietz, S., Rauber, J. & Reisch, L. A. Nudging healthier food choices in a cafeteria setting: A sequential multi-intervention field study. *Appetite* **160**, 105106 (2021).
52. Balcombe, K., Fraser, I., Lowe, B. & Souza Monteiro, D. Information Customization and Food Choice. *American Journal of Agricultural Economics* **98**, 54–73 (2016).
53. Clark, M. A., Springmann, M., Hill, J. & Tilman, D. Multiple health and environmental impacts of foods. *Proc. Natl. Acad. Sci. U.S.A.* **116**, 23357–23362 (2019).
54. Faccioli, M. *et al.* Combined carbon and health taxes outperform single-purpose information or fiscal measures in designing sustainable food policies. *Nat Food* **3**, 331–340 (2022).
55. International Food Policy Research Institute. *2022 Global Food Policy Report: Climate Change and Food Systems*. https://ebrary.ifpri.org/digital/collection/p15738coll2/id/135889 (2022) doi:10.2499/9780896294257.
56. Prag, A., Lyon, T. & Russillo, A. *Multiplication of Environmental Labelling and Information Schemes (ELIS): Implications for Environment and Trade*. https://www.oecd-ilibrary.org/environment/multiplication-of-environmental-labelling-and-information-schemes-elis_5jm0p33z27wf-en (2016) doi:10.1787/5jm0p33z27wf-en.
57. von Bloh, W. *et al.* Implementing the nitrogen cycle into the dynamic global vegetation, hydrology, and crop growth model LPJmL (version 5.0). *Geosci. Model Dev.* **11**, 2789–2812 (2018).
58. Scholes, R. J. & Biggs, R. A biodiversity intactness index. *Nature* **434**, 45–49 (2005).
59. Purvis, A. *et al.* Chapter Five - Modelling and Projecting the Response of Local Terrestrial Biodiversity Worldwide to Land Use and Related Pressures: The PREDICTS Project. in *Advances in Ecological Research* (eds. Bohan, D. A., Dumbrell, A. J., Woodward, G. & Jackson, M.) vol. 58 201–241 (Academic Press, 2018).

60. Baumstark, L. *et al.* REMIND2.1: transformation and innovation dynamics of the energy-economic system within climate and sustainability limits. *Geosci. Model Dev.* **14**, 6571–6603 (2021).
61. Springmann, M. Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. *The Lancet Planetary Health* **2**, e451–e461 (2018).
62. GBD 2019 Demographics Collaborators. Global age-sex-specific fertility, mortality, healthy life expectancy (HALE), and population estimates in 204 countries and territories, 1950–2019: a comprehensive demographic analysis for the Global Burden of Disease Study 2019. *The Lancet* **396**, 1160–1203 (2020).
63. Aune, D. *et al.* Fruit and vegetable intake and the risk of cardiovascular disease, total cancer and all-cause mortality—a systematic review and dose-response meta-analysis of prospective studies. *International Journal of Epidemiology* **46**, 1029–1056 (2017).
64. The Global BMI Mortality Collaboration. Body-mass index and all-cause mortality: individual-participant-data meta-analysis of 239 prospective studies in four continents. *The Lancet* **388**, 776–786 (2016).
65. Schwingshackl, L. *et al.* Food groups and risk of colorectal cancer: Food groups and colorectal cancer. *Int. J. Cancer* **142**, 1748–1758 (2018).
66. Bechthold, A. *et al.* Food groups and risk of coronary heart disease, stroke and heart failure: A systematic review and dose-response meta-analysis of prospective studies. *Crit. Rev. FoodSci. Nutr* **59**, 1071–1090 (2019).
67. Yuan, Y.-Q. *et al.* The Development of a Chinese Healthy Eating Index and Its Application in the General Population. *Nutrients* **9**, 977 (2017).
68. Ren, Y., Zhao, J., Glauben, T. & Castro Campos, B. Supermarket environment and nutrition outcomes: Evidence from rural China. *Journal of Rural Studies* **92**, 79–92 (2022).
69. Stubbendorff, A. *et al.* Development of an EAT-Lancet index and its relation to mortality in a Swedish population. *The American Journal of Clinical Nutrition* **115**, 705–716 (2022).
70. Rao, N. D., Sauer, P., Gidden, M. & Riahi, K. Income inequality projections for the Shared Socioeconomic Pathways (SSPs). *Futures* **105**, 27–39 (2019).
71. FAOSTAT. Database collection of the Food and Agriculture Organization of the United Nations. (2015).
72. Kreidenweis, U. *et al.* Afforestation to mitigate climate change: impacts on food prices under consideration of albedo effects. *Environ. Res. Lett.* **11**, 085001 (2016).