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Coordinated pathways to a low-carbon, healthy, and equitable food system in China

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ABSTRACT

Tackling the ongoing challenges of food insecurity and nutritional deficiencies may complicate efforts to reduce carbon emissions within the food system, a critical component of meeting the climate target. Spatial disparities in food distribution further intensify existing inequalities. This study enhances a widely used regional integrated assessment model by incorporating a novel bottom-up lifecycle assessment framework for China's food system at the provincial level. It evaluates trade-offs and explores synergies across strategies aimed at balancing healthy diets, low carbon emissions, and reduced inequalities through 2060. The results indicate that implementing single mitigation measures may increase food costs and exacerbate inequality without achieving the target carbon emission mitigation goal. However, a coordinated approach integrating actions across the supply chain, consumer demand, and land management transformation could reduce greenhouse gas emissions by 41.7%, improve nutritional quality by 24.4%, and decrease inequality by 21.9% by 2060. This study highlights the need for a cross-sectoral and regionally coordinated food system framework to achieve the climate target, ensure adequate nutrition, and foster an affordable, equitable food system.

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1. Introduction

The ongoing challenges of food insecurity and nutritional deficiencies, which affect about 9.1% of the global population [1], could complicate efforts to reduce carbon emissions within the food system, a critical step toward meeting the 1.5 °C target [2,3]. Production-side interventions, such as planting pattern optimization and innovative management, can mitigate carbon emissions and environmental impacts [4,5], improving farmers' welfare [6],

while supply-side strategies should closely align with the growing food demand [7]. On the consumption side, dietary transitions are identified as having the highest potential for emission mitigation [8–11]. However, most national dietary guidelines primarily focus on health, with only a few mentioning environmental sustainability recommendations [12–15], leading to conflicts between improving nutrition and reducing carbon emissions [15–17]. For example, adhering to the EAT-Lancet recommendations aimed at improving planetary and human health could reduce food affordability due to inadequate supplies of healthy food [18,19]. In China, following the Chinese Dietary Guidelines (CDG) could even increase emissions by 2.5 Gt CO₂e per year, a 7.5% rise from the baseline [16,20]. Therefore, beyond isolated actions on food

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production or consumption, integrated and holistic strategies are necessary to achieve both low-carbon and health co-benefits within the food system [21–24].

Food systems, understood as coupled human–natural systems [25], exhibit cross-scale feedbacks between biophysical processes and societal dynamics within the sustainability science perspective [26]. Across the entire lifecycle, the food system integrates a spatial nexus linking production landscapes, interregional supply chains, consumption patterns, and their associated environmental outcomes and social well-being [27]. Regional distribution disparities within the food system, driven by the spatial heterogeneity of natural resource endowments, further complicate the efforts to achieve environmental and social sustainability [28–30]. Production-intensive regions, often focused on food exports, bear a disproportionate share of emissions resulting from carbon-intensive consumption patterns in food-importing regions [31,32]. This imbalance undermines both environmental sustainability and social well-being [33,34] at international and sub-national levels [35,36]. In China, food system distribution disparities are exacerbated by market-driven supply and demand dynamics, with cropland displacement [37] within the national food system further intensifying these challenges [35]. As shifts in supply and demand deepen regional disparities [38,39], coordinated approaches are essential to integrate the supply and demand sides of the food supply chain [40], particularly to address the inequalities caused by shifting food distribution patterns. Health, sustainability, and justice are the transformation goals for the planetary food systems [41]. So far, efforts to achieve co-benefits often overlook inequality issues [42,43], and it remains unclear whether integrated strategies aimed at both climate mitigation and health improvement can effectively address inequalities.

However, the food system, encompassing production, processing, distribution, transportation, consumption, and waste disposal, is rarely modeled comprehensively across its entire lifecycle [33,44]. Current models often overlook the potential of coordinated approaches and cross-sectoral synergies [45]. Given the interconnected nature of the food supply chain [46], adopting holistic and dynamically integrated strategies is essential for addressing systemic challenges and achieving co-benefits [45–47]. However, it remains unclear whether the integrated strategies will enhance these outcomes. This is particularly relevant for China, where the rapidly evolving food supply chain [48] necessitates an integrated approach to balance food security with climate mitigation across the entire lifecycle of the food system [49,50]. Effective coordination assessment requires more than aggregating the potential of single actions [49]; it demands a deeply embedded, well-structured integration such as system dynamics or integrated assessment within the food supply chain to deliver meaningful, practical outcomes.

To address the knowledge gaps related to inequality and the pursuit of co-benefits in emissions reduction and health improvement, this study presents a novel “bottom-up” approach. It develops a region-specific lifecycle GHG emission factor dataset and an integrated assessment model tailored to China's food system, and explores coordinated-action pathways for mitigating GHG emissions and promoting healthy diets by 2060. The analysis quantifies the synergies and trade-offs of various scenario combinations and their effects on environmental and social inequalities. The findings offer policymakers valuable insights into achieving a low-carbon, healthy food system without exacerbating inequalities. This research lays the groundwork for an integrated framework that aligns the triple goals of achieving the global warming target of 1.5 °C, promoting healthy diets, and reducing inequality within and across regions.

2. Materials and methods

2.1. System boundary of the China's food system

The assessment of China's food system (Text S1 online for the definition of the food system) includes 12 primary food categories commonly consumed by the Chinese population. These categories consist of five plant-sourced foods (rice, wheat, maize, vegetables, and fruit), six animal-sourced foods (pork, beef, mutton, poultry, egg, and milk), and an aggregate category for aquatic food, which includes fish, shrimp, crab, shellfish, and algae. Together, these 12 food categories provide 85.4% of the total calorie intake and 88.7% of the total protein intake for the Chinese population [51]. In line with the EU's (2020) Farm-to-Fork Strategy [52], the food supply chain in this study is divided into three key stages: pre-production (extraction of the resources needed to produce agricultural products), production (land and farm management practices during food production processes), and post-production (processing, transportation, packaging, distribution, retail, household refrigeration and cooking) (Figs. S1 and S2 online). The carbon emissions from food loss and waste throughout the entire food supply chain were estimated using loss and waste ratios and the accounting methods developed by Xue et al. [53] and Niu et al. [54]. The accounting results show good consistency with the existing food system emission accounting results (Tables S1 and S2 online).

2.2. Integrated assessment model of China's food system lifecycle

Life Cycle Assessment (LCA) is a widely used method, following the standardized ISO 14040 framework, for evaluating the environmental burdens associated with a product, process, or activity [55]. The LCA of the food system includes the entire lifecycle of food, encompassing preproduction, production, and post-production processes. The emission factors of each process unit in LCA estimation mostly come from the IPCC, research publications and LCA datasets (Data S1 online). The consumption and activity data of each process come from statistical yearbooks at the provincial level, food industrial reports, and estimations within the literature (Text S2 Data sources and Table S3 online). Emission factors in almost all production stages are set at the provincial level, while those in the post-production stage are mostly at the national scale (Data S2 online), and all activity data are at the provincial level (Data S3 online).

Based on the food system lifecycle framework, this study improves a widely-used integrated assessment model for Chinese agriculture, known as China Agricultural Policy Simulation Model (CAPSiM) [35,56,57], to systematically simulate future dynamics of GHG emissions within China's food system. The food system lifecycle integrated assessment model (FSLIAM) (Fig. 6) primarily comprises the Provincial Production and Consumption Functions, Supply-Demand Equilibrium Functions, the Net Social Revenue (NSR) maximization module, and the food system lifecycle GHG emissions accounting module (Text S3 online). The integrated assessment model is built upon two fundamental assumptions. First, we assume market equilibrium where all provinces operate within an interconnected domestic market subject to uniform price-influencing factors, causing proportional and simultaneous price changes across regions. Second, we exclude cross-price substitution effects between food types due to their negligible long-term explanatory power. These assumptions ensure computational tractability while preserving model validity for long-term food system projections.

The FSLIAM improves upon CAPSiM in several ways. (1) Provincial-level data integration. We enhanced the model by incorporating food supply, demand, and price data at the provincial level. By relying on provincial level cost and benefit data compilation and food price data, we downscaled the national model to reflect regional differences across provinces. The elasticities of production and consumption functions at the provincial level are derived from the empirical data between 1990 and 2015. The model was first calibrated using historical data from 1990 to 2015. The calibrated model was tested/validated by comparing the predicted values for 2018 with real data in 2018 (Text S4 Model validation and Table S4 online).

(2) Inter-provincial and international trade. In addition to achieving equilibrium on provincial markets, the model simulates inter-provincial and international trade. The model includes 31 regions and 12 food categories. A NSR maximization module was added to estimate the total import and export of each food type for each province [58]. This module considers the transportation costs between regions and maximizes the producer and consumer surpluses while minimizing the cost of transporting products across regions.

Objective function:

$$\text{Max} \left(\text{NSR} = \sum_{i=1}^N \text{MIQ}_i * P_i - \sum_{j=1}^{31-N} \text{MOQ}_j * P_j - \sum_{i=1}^N \sum_{j=1}^{31-N} c_{ij} * z_{ij} \right). \quad (1)$$

Subject to the following constraints:

$$\sum_{i=1}^N z_{ij} \geq \text{MIQ}_j, \quad (2)$$

$$\sum_{j=1}^{31-N} z_{ij} \leq \text{MOQ}_i, \quad (3)$$

$$(z_{ij}, \text{MIQ}_i, \text{MOQ}_j) \geq 0, \quad (4)$$

where MIQ_i is the food shortage in the region i (1×31), MOQ_j is the food surplus in the region j (1×31), i is the food shortage region, j is the food surplus region, N is the total number of shortage provinces, z_{ij} is the sale (31×31) from food surplus area j to food shortage area i , P_i is the food price in the region i (1×31), P_j is the food price in the region j (1×31), and c_{ij} is the food transportation cost from provinces i to j . Based on the *National Social Food Supply and Demand Balance Survey Table in 2018* obtained from the National Food and Strategic Reserves Administration, this study also adjusted the model to ensure that the inter-regional food trade matrix from the model's operation matches the quantities of food inflows and outflows in 2018 for each type of food at the provincial level.

(3) Scenario-based optimization. The scenario-based optimization objective function aims to minimize total food system GHG emissions across the entire lifecycle of 12 food types and 31 regions towards 2060, while taking into account constraints such as reserve arable land, agro-climatic yield potential, and regional water scarcity. The model incorporates various scenario settings (Fig. 6), including exogenous variables such as dietary patterns (used in the CDG and the EAT scenarios), farm size, food loss and waste ratios, international imports and exports, land reclamation, and production emission intensities (Text S5 online for more details).

The model outputs include lifecycle emissions of the entire food supply chain, food affordability, and cropland expansion projections. Food affordability is defined as the share of total food expenditure in total income. Food consumption expenditure is calculated as the product of food prices and food consumption quantities, which are outputs of the model and considered endogenous variables, while income is derived from SSP outputs [59] and is exogenous to the model. As a scenario-based integrated assessment

model, it internalizes economic and social outputs from the SSP framework to form a long-term dynamic evaluation for 2060. The model is executed in the General Algebraic Modeling System (GAMS), a high-level platform for mathematical optimization.

The business as usual (BAU) scenario follows the Shared Socio-economic Pathway 2 (SSP2), which is regarded as mostly aligning with the current development trends in population, economy, technology, and resource use [60,61]. Under SSP2, China is expected to gradually reduce its dependence on fossil fuels, with its population peaking at 1.4 billion around 2035 and urbanization reaching 80% by 2050. The population in 2060 is projected to be 1.36 billion. This study revised the population data of SSP2 based on China's seventh population census conducted in 2020. All other single action scenarios in this study use the BAU (SSP2) as the reference.

Two key dietary scenarios were examined: one involves adopting the Dietary Guidelines for Chinese Residents (CDG) issued by the Chinese Nutrition Society [62], and the other involves adopting the EAT-Lancet dietary patterns recommended by the EAT-Lancet Commission [18]. Dietary shifts in both the scale and structure of consumption significantly affect GHG emissions from the food system. Table S5 (online) reports the recommended intake values for different food types according to the CDG and EAT guidelines. Given the large gap in milk consumption, trend growth forecasts were used to project future milk intake.

The Technology (TEC) scenario is based on comparing the carbon footprints of various types of food production in China and globally, with the aim of adopting the best-practice low-carbon production technologies by 2060. The TEC scenario assumes optimal and frictionless technology diffusion. For China's carbon intensity in food production, we utilized the carbon emission intensity database for food in China constructed for this study (Data S2 online). The GHG emissions intensities of other countries were derived from the global database provided by Clune et al. [63]. It acknowledges that real-world barriers, including adoption costs, intellectual property restrictions, infrastructure requirements, and institutional constraints, would affect technology implementation.

The Optimization (OPT) scenario focuses on optimizing agricultural production locations and cropland expansion to minimize GHG emissions while meeting consumption demand. Given the spatial differences in climate, soils, and farm management practices (e.g., energy use, fertilizer application) [46], there are substantial regional variations in the carbon footprint of agricultural production [64]. Thus, this scenario employs region-specific mitigation measures [6]. It considers the potential for cropland expansion in low-carbon, undeveloped areas and seeks to minimize total food supply chain emissions, constrained by reserve arable land (area) and agro-climatic yield potential (productivity), as set by the GAEZ (Global Agro-Ecological Zones) model. The GAEZ model assesses the best attainable yield of individual crops on each grid-cell of suitable land, which takes into account climate conditions, soil moisture deficits, and management input levels [65].

The Imports (IMP) scenario explores the potential for increasing food imports to mitigate GHG emissions within China's food system. According to projections from OECD-FAO (<https://stats.oecd.org/index.aspx?queryid=71240>), China's imports of livestock, poultry, meat and dairy products are expected to increase, with livestock and poultry food imports rising by 24.8% and dairy imports by 27.7% by 2025 compared to 2018. This study extends the OECD-FAO trend projections from 2025 to 2060, with future imports constrained by the supply capacities of potential exporter partners (Table S6 online).

The Farm Size Expansion (FAR) scenario considers the relationship between farm size and the application of pesticides and fertilizers. Empirical studies show that larger farms tend to use fewer

chemical inputs per hectare, which in turn reduces GHG emissions [66]. This scenario calculates changes in pesticide and fertilizer use based on projected increase in average household farm size and estimates the resulting emissions reductions.

The Loss and Waste Reduction (LLS) scenario aligns with the SDG target 12.3, which aims to halve global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses, by 2030. This scenario assumes a 50% reduction in food loss and waste every 10 years from 2030 to 2060. The model simulates equilibrium solutions for food supply and demand, as well as the resulting emissions reductions from lower demand and improved supply efficiency.

2.3. Nutritional quality evaluation by Alternative Healthy Eating Index (AHEI)

The Alternative Healthy Eating Index (AHEI) is a widely used dietary quality assessment indicator developed by Harvard T.H. Chan School of Public Health, that aim to evaluate the quality of diets, and has been updated periodically to reflect the latest scientific evidence on diet-health relationships [67]. It comprises two component categories. (1) Adequacy Components promote beneficial elements, including vegetables, fruits, whole grains, nuts and legumes, long-chain omega-3 fatty acids, and Polyunsaturated Fatty Acids (PUFAs). Higher intake of these components results in higher scores. (2) Moderation Components should be consumed in limited quantities, including red and processed meats, sugary beverages, sodium, and alcohol. Lower intake of these components results in higher scores. Each component is scored from 0 to 10 with intermediate intake levels scored proportionally. Since beverages and alcohol were excluded from this study's food system boundaries, the total possible score ranged from 0 to 90. Higher scores indicating better dietary quality aligned with recommendations. The AHEI uses density, intake per 1000 kcal, making it adaptable across different energy needs without adjustments for age, sex, or physical activity. This approach normalizes intake relative to total energy consumption, ensuring comparability across diverse populations.

2.4. Theil index for regional inequality assessment

The Theil index developed by economist Henri Theil is a statistical measure designed to quantify inequality within a region. It is particularly effective for assessing disparities in income distribution among different groups or across geographical areas [68,69]. This study employs the Theil index to calculate provincial-level disparities in food system emissions and food expenditures, separately, by using outputs from the integrated assessment model. Accordingly, “societal inequality” in this study is defined as “regional inequality in food affordability”, and “environmental inequality” in this study is defined as “regional inequality in food system emissions”. These calculations help measure the environmental and social inequalities arising from combined action strategies. The Theil index is computed using the following formula:

$$T = T_w + T_b, \quad (5)$$

$$T_w = \sum_{ij} \left(\frac{y_{ij}}{\bar{y}_i} \right) \ln \left(\frac{y_{ij}}{\bar{y}_i} \right), \quad (6)$$

$$T_b = \sum_j \left(\frac{y_j}{\bar{y}_j} \right) \ln \left(\frac{y_j}{\bar{y}_j} \right), \quad (7)$$

where T denotes the total Theil index; T_w and T_b are the Theil indices for within-region and between-region inequalities, respectively; i and j refer to the province i in the region j ; y_i represents

the impact including emissions, cropland expansion, or food expenditures of the province i ; $\bar{y}$ is the mean impacts. The Theil index can be decomposed into within-group and between-group inequality components, making it particularly valuable for understanding the sources of regional inequality. A Theil index value of 0 indicates perfect equality, while higher values signify greater inequality. This index's sensitivity to changes in different segments of impacts distribution makes it an excellent tool for evaluating the effectiveness of mitigation strategies aimed at reducing inequality.

2.5. Uncertainty

The uncertainty analysis in this study adheres to the IPCC Guidelines for National Greenhouse Gas Inventories, focusing on good practices and uncertainty management [70]. Uncertainties stem from various sources, such as regional differences in production process data, emission factors from literature, and spatial allocation of transport emissions. Regarding scenario uncertainty, there is significant uncertainty in both the EAT and CDG guidelines, mainly due to the considerable uncertainty in the intake amounts recommended by EAT-Lancet and Chinese Dietary Nutrition Guidelines (2022). The 95% confidence interval (CI) simulation informs the upper and lower range of all scenarios (Text S6 online).

To assess uncertainty, empirical distribution functions were established for activity and emission factors, and appropriate probability density function models were selected. The Monte Carlo method was used to calculate the established probability density function 1000 times, determining the 95% CI range for each food type in different stages (Text S7 online). Following IPCC Guidelines [70], uncertainties were combined and transmitted through two types of methods, applicable to merging unrelated or related emission sources, as specified in Eqs. (8) and (9):

$$U_{total} = \sqrt{U_1^2 + U_2^2 + U_3^2 + \dots + U_n^2}, \quad (8)$$

$$U_{total} = \sqrt{\frac{(U_1x_1)^2 + (U_2x_2)^2 + \dots + (U_nx_n)^2}{(x_1 + x_2 + \dots + x_n)^2}}, \quad (9)$$

where U_{total} denotes the combined uncertainty, U_i the uncertainty of each functional unit, and x_i the activity value of each unit.

2.6. Data source

This study compiles comprehensive datasets for China's food system lifecycle analysis across 31 provinces, categorized into three main components (Table S2 online). (1) Parameters for China's food system lifecycle. Socioeconomic parameters including per capita GDP, urbanization rates, and Consumer Price Index were sourced from national and provincial statistical yearbooks. Food prices from China Price Yearbooks enabled monetary-to-physical quantity conversions. Lifecycle emission parameters were derived from IPCC 2006 National GHG Inventory Guidelines, China's Provincial GHG Inventory Compilation Guide 2011, and peer-reviewed literature. Electricity emission factors utilized regional power grid baselines from the National Development and Reform Commission (Data S1 online). (2) Emission factors of China's food system lifecycle. Regional and food-type-specific emission factors were calculated using production data from national agricultural cost-benefit surveys, covering fertilizer application rates, seed usage, pesticide dosages, fuel consumption, and production coefficients (Data S2 online). (3) Activity data of China's food system lifecycle encompass production and consumption statistics for 12 food types from China Statistical Yearbooks and provincial yearbooks (Data S3 online). Data processing involved disaggregating

aggregated consumption categories using regional consumption patterns (Text S8 online).

3. Results

3.1. Existing inequalities and gaps of GHG emissions and dietary quality in China's food system

Over the past three decades (1990–2023), China's food system transformation has not only led to a 19.0% improvement in residential dietary quality, as measured by the AHEI, but also a significant 115.2% rise in GHG emissions. The GHG emissions from the full lifecycle of China's food system increased from 0.94 (± 0.36) Gt CO₂e a⁻¹ in 1990 (CO₂ equivalent, GHGs were converted into CO₂ equivalent according to the 100-year Global Warming Potential, as specified in IPCC AR5, with 95% confidence interval

in the parentheses) to 2.03 (± 0.77) Gt CO₂e a⁻¹ in 2023 (Fig. 1a; and Table S7 online for a detailed discussion on the uncertainty). The increase in emissions is primarily attributed to the consumption of carbon-intensive animal-based food, which accounted for 56.3% in 2023, as well as the rapid development of the supply chain in the post-production stage, which accounted for 43.0% in 2023 (Fig. 1c). Meanwhile, the AHEI has risen from 53.6 scores (out of a total of 90 scores) in 1990 to 63.8 scores in 2023, mainly due to a 4.1-fold increase in the consumption of PUFA-rich aquatic food and a 4.6-fold increase in fruit consumption (Fig. 1b). China's rapid urbanization has intensified food system mitigation pressures, with urban food system carbon emissions escalating from 0.26 Gt CO₂e a⁻¹ in 1990 to 1.33 Gt CO₂e a⁻¹ in 2023—a 4.2-fold increase that constitutes the primary driver of China's food system emissions growth (Fig. 1a). Concurrently, urbanization-induced improvements in dietary consumption patterns have yielded a

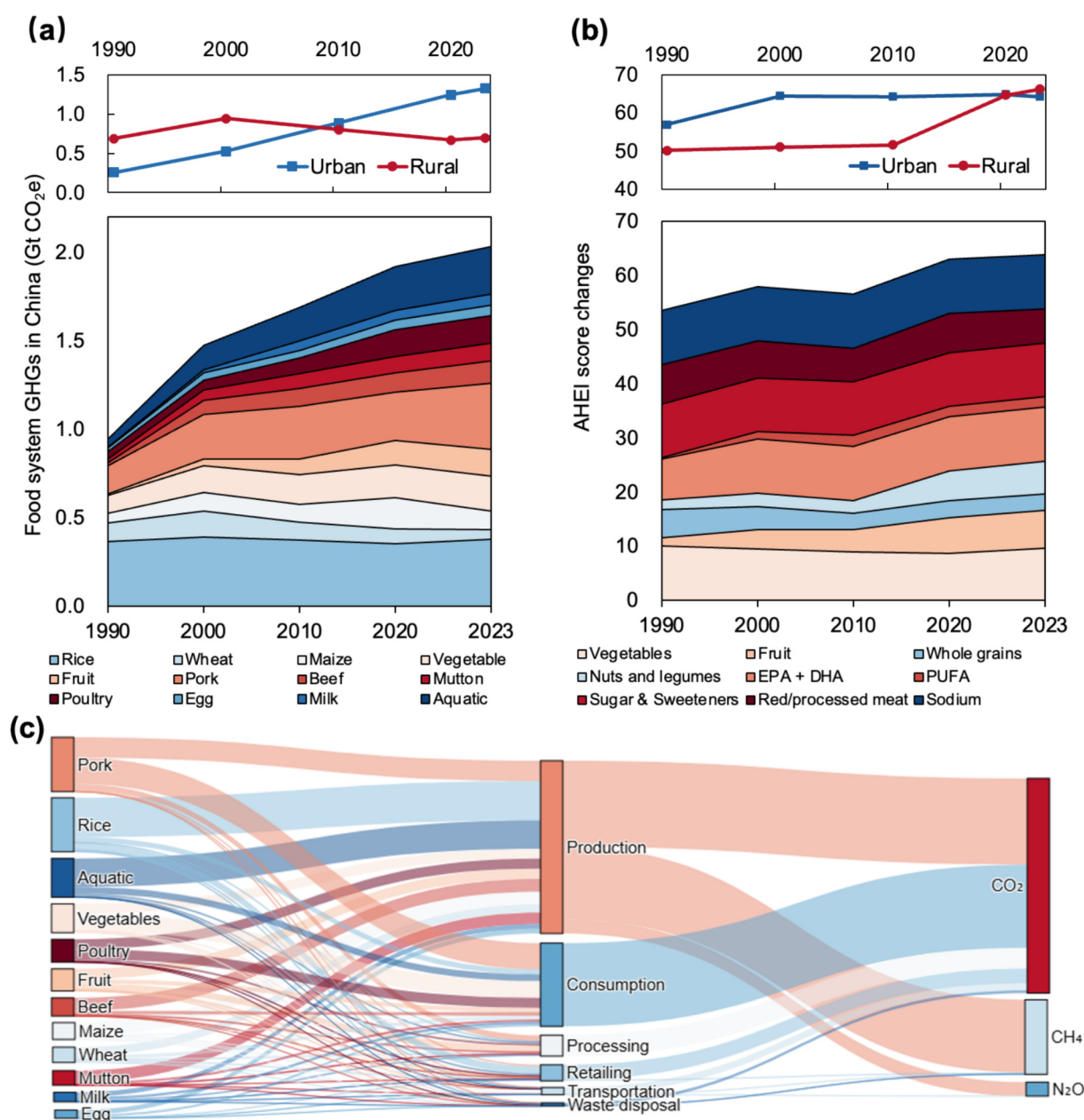


Fig. 1. The lifecycle carbon emissions and AHEI trends of China's food system. (a) The pattern changes in China's food system carbon emissions from 1990 to 2023. (b) The pattern changes in the Alternative Healthy Eating Index (AHEI) across China's food system from 1990 to 2023. (c) Sankey diagram of GHG emissions, representing the linkages among GHGs, food commodities and stages of supply-chain in 2023.

substantial 32.1% enhancement in rural residents' AHEI scores between 1990–2023, while urban residents' dietary quality has remained largely stagnant since 2000 (Fig. 1b). These divergent trajectories underscore the urgent imperative for comprehensive structural transformation of China's food systems to achieve carbon mitigation and health co-benefits.

This food system transformation has also exacerbated regional inequalities, with GHG emissions from food systems rising significantly in both southern (112.8%) and northern (122.5%) parts of the country. Northwest China (NW) saw the highest emissions growth rate at 173.5%, largely driven by a 4.3-fold increase in meat-related emissions (Fig. 2a). In terms of the AHEI changes, Hebei in North China saw the most substantial improvement at 27.9 scores (90 scores in total) mainly due to increases in long-chain omega-3 and polyunsaturated fatty acids, while Qinghai in Northwest China exhibited the slowest growth of only 5.8 AHEI scores (Fig. 2b). Therefore, China faces trade-off in regions like Northwest China, where food-related carbon emissions have increased without corresponding adequate nutritional gains.

Despite these improvements, there remains a substantial gap between current dietary quality and the recommendations of healthy dietary guidelines, which could result in further carbon emissions increases. Simulations comparing BAU food consumption with the CDG, recommended by the Chinese Nutrition Society, and the planetary healthy diet (EAT), advocated by the EAT-Lancet Commission, reveal significant nutrition discrepancies. These gaps are most pronounced in the consumption of dairy, vegetables, fruits, eggs, and aquatic products. Additionally, the intake of three major macronutrients—protein, fat, and carbohydrates—falls short by 23.1%, 30.3%, and 7.8%, respectively (Fig. S3 online). If adopted, the CDG could improve dietary quality by 9.5%, while adherence to the EAT could result in a 24.4% improvement (Fig. 2d). However, these dietary shifts have varying impacts on GHG emissions. Implementing the CDG would result in a 22.8% increase in emissions compared to the BAU, whereas adherence to the EAT could lead to a 10.3% reduction in emissions (Fig. 2c). These findings highlight the complex trade-offs between improving dietary quality and mitigating environmental impacts.

Regional disparities further complicate these trade-offs. All regions' AHEI scores fall below the EAT-Lancet recommendations, with the largest gap observed in Northwest China at 36.0%, reaching as high as 67.9% in Qinghai Province. However, East China and Northeast China's AHEI scores surpass the CDG, by 3.2% and 4.3%, respectively, notably Shanghai in East China exceeding the CDG by 10.7%. The Northwest region still exhibits a 19.7% gap between its average AHEI and the CDG. Despite this, almost all regions would encounter an increase in carbon emissions by adopting the CDG, with the Northwest experiencing the most substantial rise, potentially by 51.9%, and Shaanxi and Ningxia facing even higher increases of 68.0% respectively. In contrast, adherence to the EAT guidelines could enable approximately 77.4% of regions (89.9% of the population) to achieve “win-win” outcomes, where both nutritional quality improves and emissions decrease. Central, the Northeast, and the East China could experience emissions reductions of 20.0%, 17.0%, and 13.9%, respectively. While EAT adoption in the Northwest region offers the greatest potential improvement in AHEI (36.0%), it presents a trade-off of a 16.9% increase in emissions (Fig. 2e and f).

3.2. Outcomes of single-action strategies for emission mitigation and healthy targets

To address the trade-off between GHGs mitigation and nutrient improvements, five additional single-action strategies were developed alongside the BAU, CDG, and EAT (see Methods; Text S5 online and Table 1 for a description of each strategy). Using the

enhanced FSLIAM (see Methods and Text S3 online for the model framework), we projected GHG emissions and food affordability under these strategies through 2060. The BAU scenario serves as the reference. Under the BAU, food system emissions are projected to reach 2.39 Gt CO₂e a⁻¹ by 2060, a 17.5% increase from current levels (Fig. 3a), while food affordability improves by 16.6%, driven by income growth (Fig. 3b).

In the BAU scenario, the transition in dietary patterns is primarily driven by urbanization and rising income levels endogenous to SSP2, which have historically increased food demand and carbon emission in China since the early 1990s. A shift to the CDG diet could result in a 22.8% increase, with the 95% CI (1.5%, 39.9%), in emissions compared to the BAU, whereas the EAT diet could reduce emissions by 10.3%, with the 95% CI (−20.9%, 7.9%) (Fig. 3a). However, these dietary transitions would negatively impact food affordability, with CDG and EAT leading to reductions of 208.3% and 41.4%, respectively, compared to the BAU (Fig. 3b). The sudden decline in affordability beginning in 2020 reflects the immediate market response to dietary policy implementation, as increased demand for higher-value nutritious foods drives up average food prices.

The TEC scenario focuses on upgrading food production with advanced low-carbon technologies. We compare the carbon footprints of various food products between China and best-practice countries. For example, aligning with Australian mutton meat production standards could reduce carbon footprints by 3.2%. Overall, TEC offers a potential emission reduction of 9.9% (±1.4%) for the total food system (Fig. 3a), with Central China exhibiting the highest reduction potential (15.9%) due to its substantially larger carbon footprint from rice cultivation (Fig. S4 online). Meanwhile, the benefit of green production technologies would improve food affordability by 7.4% through reducing the cost of production inputs (Fig. 3b), with Southwest China facing an increase at 17.1% (Fig. S5 online).

The FAR scenario links farm size expansion to reductions in pesticide and fertilizer use. Empirical studies show that a 1% increase in farm size is associated with a 0.3% and 0.5% decrease in pesticide and fertilizer use [66], respectively. Farm size is expected to grow under the BAU due to rural depopulation and land transfer. FAR could reduce carbon emissions by 4.1% (±2.8%) (Fig. 3a), with Heilongjiang in Northeast China showing the greatest potential at 30.2% owing to significant expansion of farm size in this major grain production province (Fig. S4 online). However, the cost reduction from farm expansion could offset cross-regional supply costs, leading to an 11.6% improvement in food affordability (Fig. 3b).

The OPT scenario optimizes the spatial distribution of crop planting and cropland reclamation to minimize lifecycle food system carbon emissions without compromising the best attainable production levels in each province. This scenario accounts for constraints such as future agro-climatic potential yield (productivity) estimated by the GAEZ model under three RCP scenarios (Fig. 3e), exploitable reserves of arable land (area) from national land survey, and irrigation limitations without increasing regional water scarcity. The OPT scenario offers a potential GHG reduction of 5.7% (±1.8%) (Fig. 3a), with the most significant reduction occurring in North, Central and Northwest China (Fig. 3c and d). This low-carbon oriented optimization is achieved through strategic spatial planning of crop locations and the reclamation of low-emission, currently unused land. For example, rice production could be expanded into currently unexploited areas in Northeast China and the Yangtze River Delta, driven by demand consideration (Fig. S4 online). However, redistribution cropland to regions with low-carbon production advantages is expected to decrease overall cross-regional supply costs through efficiency gains, leading to an 1.8% improvement in food affordability compared to

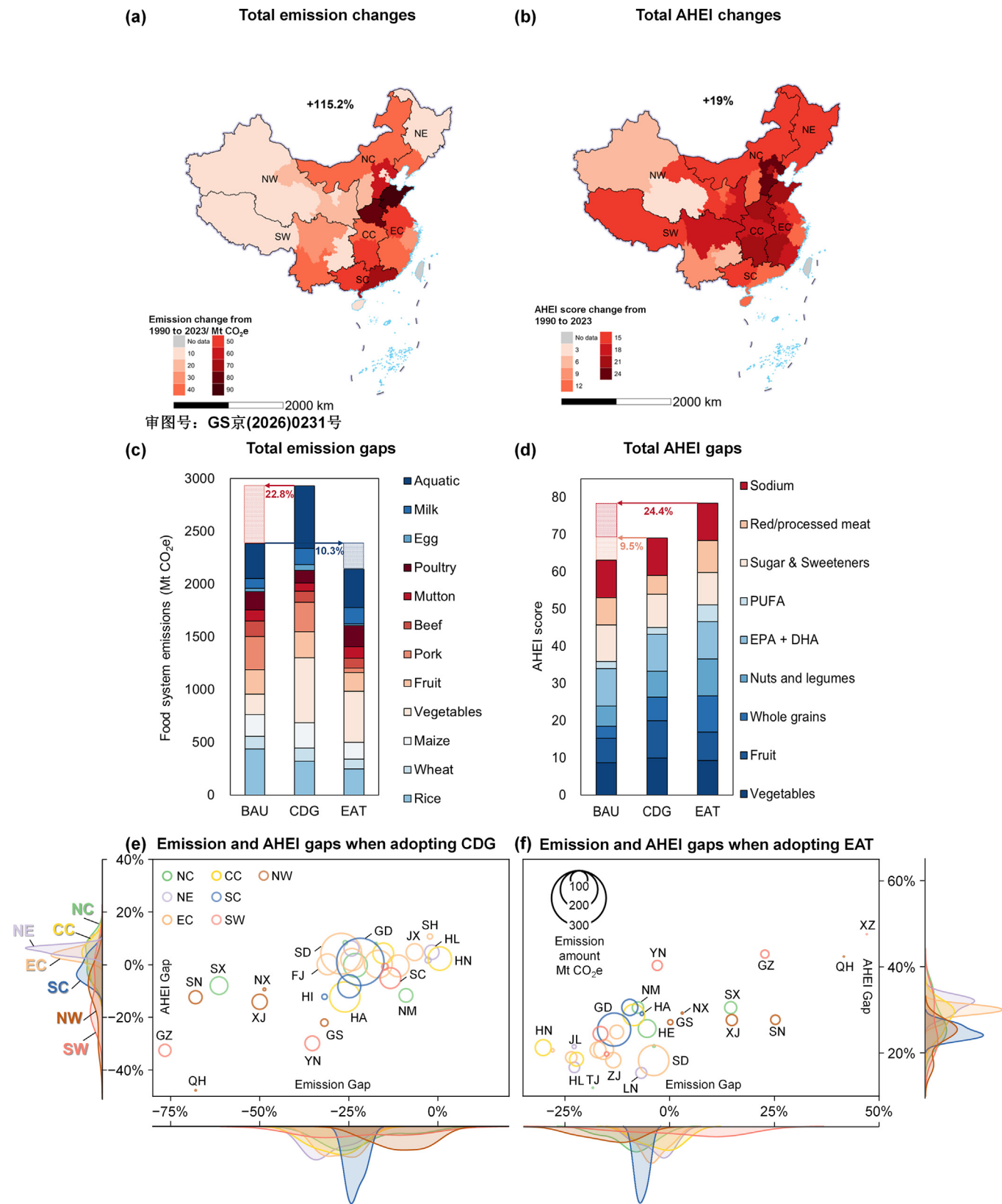


Table 1
Brief description of single and combined action strategies.

Type	No.	Strategy	Stakeholder	Description
Consumption Transformation	CDG	Chinese Dietary Guidelines	Consumers	Dietary transition following Chinese Dietary Guidelines
	EAT	EAT-Lancet planetary healthy diet	Consumers	Dietary transition following EAT-Lancet Guidelines
Supply Chain Transformation	LLS	Reducing food loss and waste	Consumers, supply chain enterprises, and government	Follows SDG 12.3 to halve FLW (food loss and waste) by 2030 and then continue this decreasing trend until 2060
	IMP	Import pattern optimization	Supply chain enterprises, and government	Import pattern optimization based on the food imports forecast from OECD-FAO, intends to explore potentials for importing meat and dairy products to China in the future
Production Transformation	TEC	Production technology upgrading	Agricultural producers, and government	Production technology upgrading focuses on upgrading food production to advanced low-carbon practice.
	FAR	Farm size expansion	Agricultural producers, and government	The farm size is expected to expand in line with the decrease in rural population under the BAU due to land transfer
	OPT	Spatial optimization for production	Agricultural producers, and government	The objective of the optimization is to minimize the entire lifecycle food system emissions without compromising the best attainable production levels in each province
Combined action strategy	1	Consumption Transformation (CDG)	Consumers, and government	Dietary transition following Chinese Dietary Guidelines while halving food loss and waste by 2030 and continuing reduction until 2060
	2	Consumption Transformation (EAT)	Consumers, and government	Dietary transition following EAT-Lancet Guidelines while halving food loss and waste by 2030 and continuing reduction until 2060
	3	Supply Chain Transformation	Supply chain enterprises, and government	Optimizing domestic food supply chain through strategic meat and dairy imports, while halving food loss and waste across the supply chain through 2060
	4	Production Transformation	Agricultural producers, and government	Transforming food production through spatial allocation, farm size expansion, and low-carbon technology upgrading to minimize lifecycle emissions
	5	Integrated strategies (CDG)	All food system stakeholders	Integration of all production-side transformation, supply chain optimization, and consumption-side transition following Chinese Dietary Guidelines
	6	Integrated strategies (EAT)	All food system stakeholders	Integration of all production-side transformation, supply chain optimization, and consumption-side transition following EAT-Lancet Guidelines

Note: Each colored box in the first column represents a single action strategy, and the combination of set of boxes represents a combined action strategy.

the BAU scenario (Fig. 3b). However, for regions that rely on long-distance food supplies, such as the Northwest, the increase in cross-regional supply costs will worsen food affordability (Fig. S5 online).

The IMP scenario, based on the food import forecasts from OECD-FAO, explores the potential for increasing imports of live-stock, poultry, meat, and dairy products to China. By selecting countries with low carbon emission intensities and sufficient export capacity (Table S6 online for potential exporter partners), the IMP scenario could mitigate GHG emissions by 12.3 Mt CO₂e a⁻¹. This includes 9.8 Mt CO₂e from importing livestock and poultry and 2.5 Mt CO₂e from importing milk, resulting in a total emissions reduction potential of 1.9% (±1.7%) (Fig. 3a, Fig. S4 online). By alleviating domestic production pressure through increased imports, the IMP scenario also improves food affordability by 24.6% compared to the BAU (Fig. 3b). This improvement is especially pronounced in regions with limited food supply capacity,

such as Southwest China, where food affordability improves by 38.4%, especially Xizang, where it increases by 63.0% (Fig. S5 online).

The LLS scenario aligns with SDG 12.3, aiming to halve food loss and waste by 2030 and continue reductions through 2060. LLS could reduce emissions by 6.8% (±1.6%) by 2060 (Fig. 3a), with Northeast and North China seeing the largest reductions at 11.3% and 10.5%, respectively (Fig. S4 online). By narrowing the supply-demand gap, LLS would significantly improve food affordability by 50.5% (Fig. 3b), with the greatest improvement in Tibet, where affordability could rise by 75.3% (Fig. S5 online).

3.3. Outcomes of combined-action strategies for climate target along the food supply chain

Fig. 4 compares the performances of all possible combined-action scenarios in mitigating GHG emissions from China's food

Fig. 2. The carbon emission and AHEI patterns of China's food system. (a) The distribution of changes in China's food system carbon emissions from 1990 to 2023, with regions categorized as Northeast China (NE), North China (NC), Northwest China (NW), East China (EC), South China (SC), Central China (CC), and Southwest China (SW). (b) The distribution of changes in the Alternative Healthy Eating Index (AHEI) across China's food system from 1990 to 2023. (c) Total emission gaps projected for 2060 under the BAU, CDG and EAT scenarios. (d) Total AHEI gaps projected for 2060 under the BAU, CDG and EAT scenarios. BAU = Business-as-usual. CDG = Chinese dietary guideline. EAT = EAT-Lancet guideline (see Table 1 for description of scenarios). (e) Regional emissions and AHEI gaps when adopting CDG in 2060. The horizontal axis represents the emission gap, and the vertical axis represents the AHEI gap. Each circle represents a province, with the size of the circle indicating the province's emission levels when adopting CDG. Colored circles represent the regions to which the provinces belong. The curve below the horizontal axis shows the distribution density of all data points on the "Emissions Gap" dimension. The curve on the left or right side of the vertical axis shows the distribution density of all data points on the "AHEI Gap" dimension. (f) Regional emissions and AHEI gaps when adopting EAT in 2060, following the same structure as in E. The name of the circles as BJ = Beijing, TJ = Tianjin, HE = Hebei, SX = Shanxi, NM = Nei Mongol, LN = Liaoning, JL = Jilin, HL = Heilongjiang, SH = Shanghai, JS = Jiangsu, ZJ = Zhejiang, AH = Anhui, FJ = Fujian, JX = Jiangxi, SD = Shandong, HA = Henan, HB = Hubei, HN = Hunan, GD = Guangdong, GX = Guangxi, HI = Hainan, CQ = Chongqing, SC = Sichuan, GZ = Guizhou, YN = Yunnan, XZ = Xizang, SN = Shaanxi, GS = Gansu, QH = Qinghai, NX = Ningxia, XJ = Xinjiang.

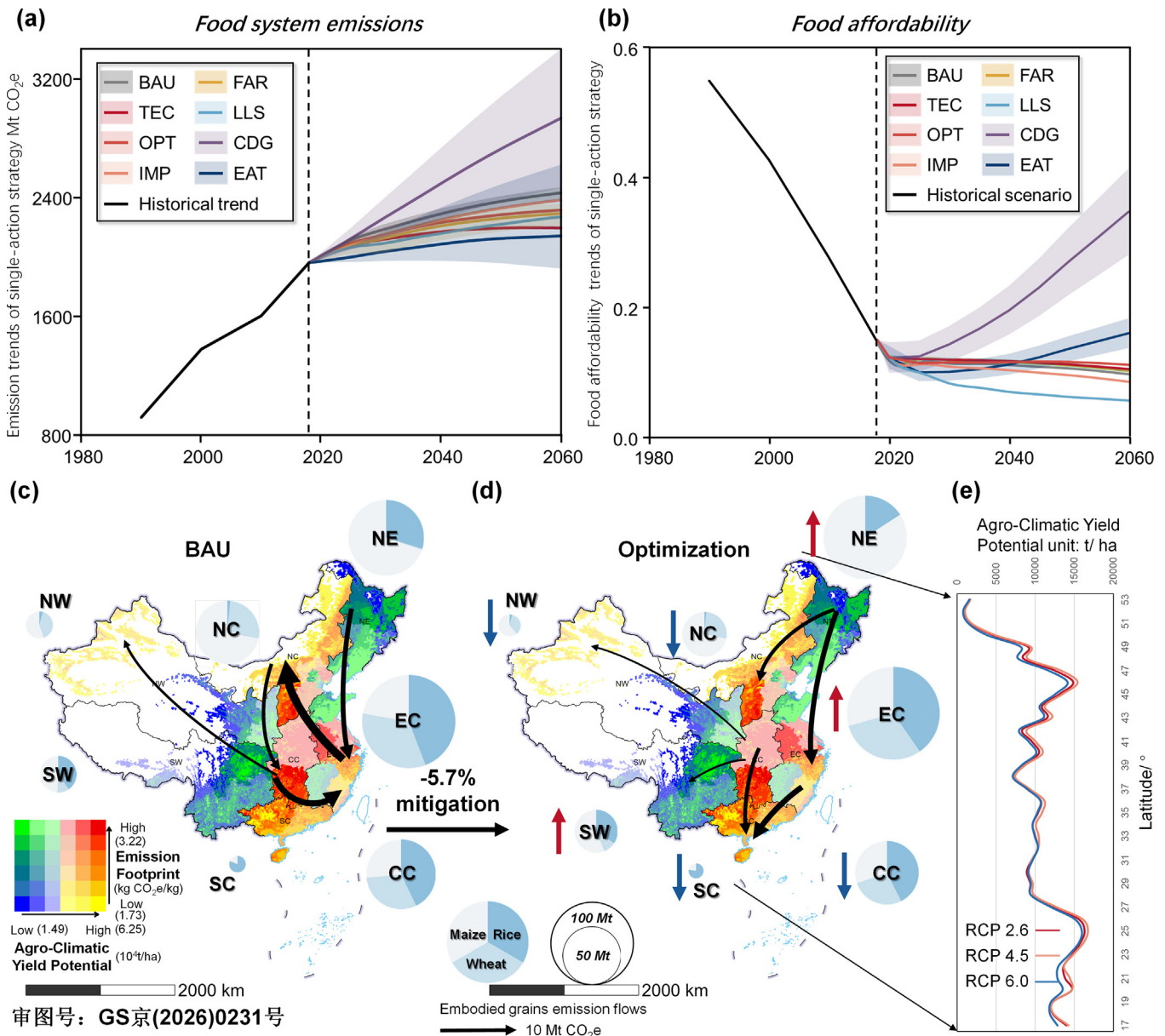


Fig. 3. Trends of carbon emission and food affordability in single-action pathways. (a, b) Historical and projected trends (2060) for food system GHG emissions (a) and food affordability (b). Colored lines represent the trends for each single-action scenario, with dashed lines and shaded areas denoting the 95% confidence intervals. BAU = Business-as-usual, EAT = EAT-Lancet guideline, CDG = Chinese dietary guideline, OPT = optimization scenario, IMP = import scenario, FAR = Farm size expansion scenario, TEC = Technology scenario, LLS = Loss and waste reduction scenario (Table 1 online for description of strategies). (c, d) Emission patterns under the business-as-usual scenario (BAU) (c) and the spatial optimization of grain production (OPT) (d) in 2060. Colors on the grid map represent the coupling or decoupling relationships between emission footprints and agro-climatic yield potential of cropland in different regions, with the color regimes specified in the four quadrants below the map. Pie charts show the structure and scale of grain production in each region. Black arrows indicate inter-regional emission flows embodied in grain trade, red arrows show increased grain production, and green arrows represent decreased production in the OPT scenario. (e) Agro-climatic potential yield of crops (2040–2080) under three RCP scenarios (2.6, 4.5, and 6.0).

system by 2060, targeting either a 1.5 °C or 2.0 °C. As shown in Fig. 2c, a dietary shift to the CDG is projected to increase emissions by 22.8%, while adoption of the EAT diet could result in a 10.3% reduction in emissions. To achieve emissions reduction under the CDG scenario, at least two or more combined-action strategies are required. The most comprehensive scenario, which integrates all available measures, could achieve up to 19.3% reduction in GHG emissions with the CDG (Fig. 4a). In contrast, all combined-action strategies under the EAT diet show emission reduction potential, with the fully integrated scenario achieving a 41.7% reduction by 2060 (Fig. 4b). Furthermore, to reveal how these combined-action scenarios contribute to the 1.5 °C or 2.0 °C climate target, we cate-

gorize them across three transformational aspects: production, consumption, and supply chains (see Table 1 for a description of each combined-action strategy). To align with global climate goals, research suggests a 67% likelihood of meeting the 2.0 °C target if cumulative emissions from food and non-food sources are capped at 1405 Gt CO₂e, and 50% chance of achieving 1.5 °C target if cumulative emissions are limited to 705 Gt CO₂e by 2100 [2]. Distributing these carbon emission limits equally per capita, China's full contribution to the 2.0 °C target would require controlling food and non-food emissions to 2.66 Gt a⁻¹ by 2060 (67% chance), while its full contribution to the 1.5 °C target would necessitate limiting emissions to 1.34 Gt a⁻¹ (50% chance). Under the BAU scenario, China's

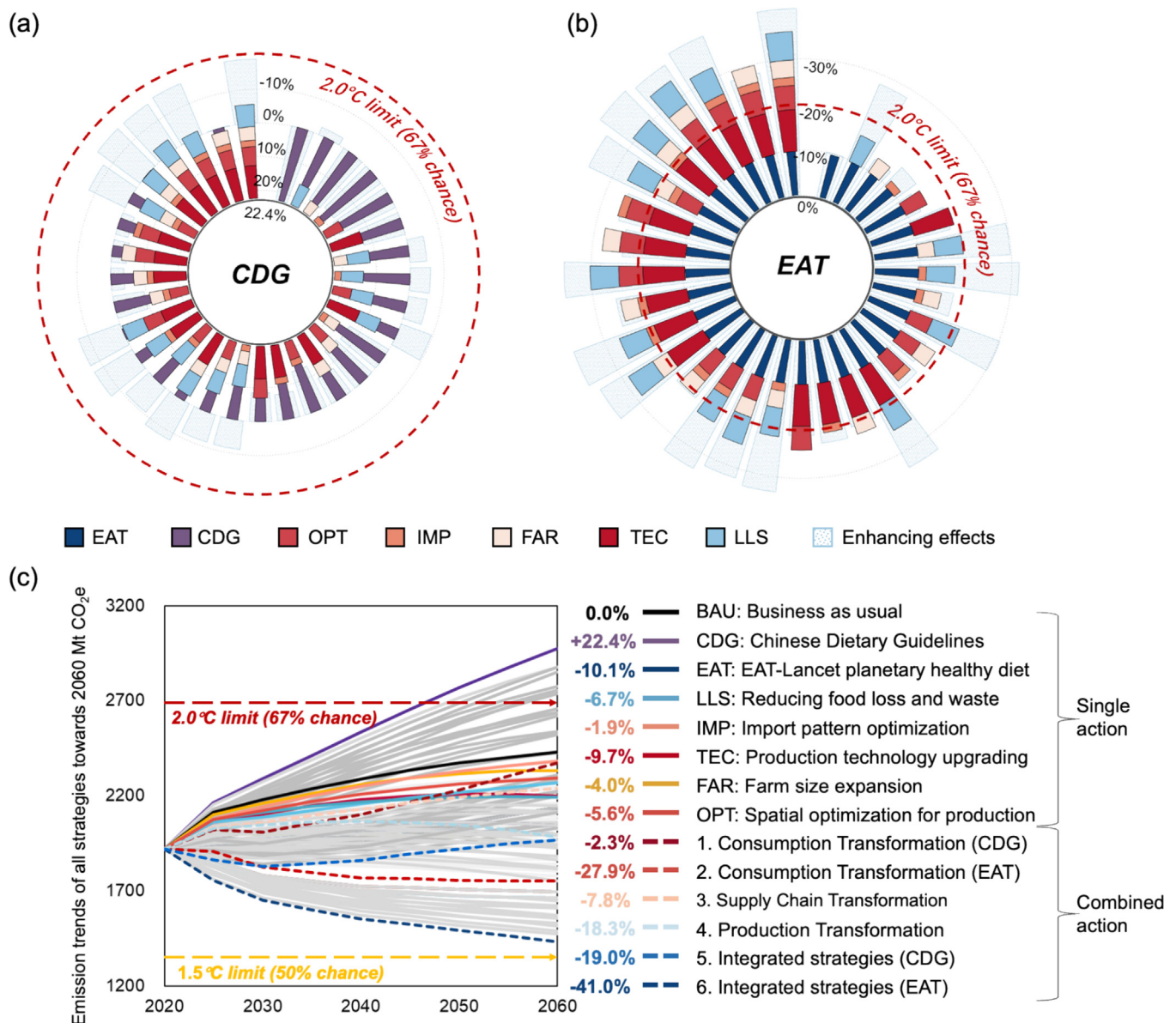


Fig. 4. Performance of combined-action scenarios in mitigating China's food system carbon emissions by 2060. (a, b) Combined-action scenarios (2060) under CDG (a) and EAT (b) adoption. The length of each color bar represents the emission reduction potential of individual single-action scenario. The stacked colored columns illustrate the cumulative emission reduction potential of each combined-action scenario. The light blue shaded areas at the outer edges of the bars represent the additional mitigation, or enhancement effects, stemming from each combined-action scenario (see Table 1 for description of strategies). (c) Mitigation potential trends of combined-action scenarios (2018–2060; in Mt CO₂e). The numbers beside each colored line indicate the emission mitigation potential of combined action strategies. The gray solid lines represent all combination scenario trends. Dashed lines represent the food and non-food mitigation targets needed to meet the 1.5 °C (orange) and 2.0 °C (red) climate goals, respectively.

food system could contribute to achieving the 2.0 °C target, though this also depends on emission reduction efforts from other sectors. However, the BAU emissions from China's food system alone would be insufficient to contribute to achieving the 1.5 °C target, meaning that achieving alignment with the 1.5 °C pathway requires at least a 43.8% reduction in food system emissions compared to the BAU scenario (Fig. 4c). This implies that China's food system emissions need significant reduction efforts to meet the 1.5 °C target. Encouragingly, if all strategies are implemented alongside the EAT diet, a 41.0% emissions reduction could be attained, bringing China significantly closer to the 1.5 °C target by 2060 (Fig. 4c). This finding highlights the critical role of integrating both demand- and supply-side measures to meet global climate goals.

An “enhancement effect” occurs when the combined actions in a strategy achieve a greater carbon emission reduction than the sum of the individual effects of each action. This additional emission reduction is achieved through lifecycle interactions within the food supply chain (Text S9 online for formulas and details). The outermost light blue shading in Fig. 4a and b represents these enhancement effects. Approximately 71.9% of the combined action strategies exhibit such enhancement effects, leveraging synergies that have previously been underestimated. In the scenario integrating all strategies under the CDG, a 13.5% enhancement effect is achieved. The greatest enhancement effect, 19.9%, results from the integration of supply chain and production transformation strategies (LLS, TEC, FAR, and IMP) (Fig. 4a).

3.4. Synergies and trade-offs considering carbon emissions and societal inequalities

Although the combined action strategies have the potential to achieve the 1.5 °C target, we should be cautious about the inequalities that may arise from emissions reductions throughout the food supply chain. In addition to the varying mitigation and enhancement effects of different combined-action scenarios, there are critical trade-offs and synergies between environmental (emissions) and societal (food affordability) inequalities based on how each strategy redistributes the food supply chain. Achieving sustainable development requires identifying multi-impact synergies that simultaneously reduce carbon emissions, improve food affordability, and decrease inequalities when compared to the BAU scenario. Therefore, implementing strategies to transition toward low-carbon, healthy food systems should consider their impacts on both carbon emissions and social inequalities.

Single-action strategies alone are insufficient to achieve synergies across carbon emissions mitigation, food affordability improvement, and inequality reduction. For example, while the CDG scenario results in a 22.8% increase in emissions, it also causes a drastic 208.3% decrease in food affordability due to the higher cost of healthy meals (Fig. 5a and n). Although the EAT-Lancet scenario reduces emissions by 10.3% (Fig. 5a), it lowers affordability by 41.4% (Fig. 5b). On the supply chain side, the LLS strategy provides triple synergies by reducing emissions (−6.8%), substantially improving food affordability (−50.5%), and decreasing both environmental (−2.1%) and societal inequality (−38.7%). However, its mitigation potential is far from sufficient to meet the 1.5 °C target (Fig. 4c). The IMP scenario achieves synergies between emissions reduction (−1.9%) and affordability improvement (−24.6%) but may exacerbate environmental inequality (+0.6%) due to its impact on domestic production (Fig. 5c). On the production side, the TEC scenario leads to a 7.4% improvement in food affordability due to abundant food supply and decreased food costs (Fig. 5b). The land-based strategy OPT, through expanding production in resource-rich regions, increases long-distance food supply, thereby raising costs and emissions and worsening regional environmental (+0.6%) and social inequalities (+1.3%) (Fig. 5c).

Integrated scenarios offer greater potential for achieving the 1.5 °C climate target, while selecting the appropriate combinations remains a challenge for achieving synergies across emissions mitigations, food affordability improvement, and inequality reduction (Strategy 4 in Fig. 5c). Regionally differentiated land management policies are therefore needed to balance these effects. While the combination of all measures can reduce emissions and inequality, the inclusion of the CDG still leads to decreased food affordability (+84.3%) due to high-cost food consumption (Strategy 5). The best coordinated pathway is represented by Strategy 6, which includes transitioning to the EAT diet and integrating all relevant measures (Fig. 5a–c). This strategy achieves a 41.7% reduction in emissions, an 18.2% improvement in food affordability, a 10.2% decrease in environmental inequality, and a 21.9% decrease in societal inequality, while bringing China much closer to the 1.5 °C target by 2060 (Fig. 4c).

4. Discussion and conclusion

Sustainable production and consumption, as advocated by SDG 12 (Responsible Consumption and Production) and the UN Food Systems Summit, are crucial for limiting GHG emissions within planetary boundaries [71]. However, the spatial heterogeneity amplified by agricultural intensification and shifting consumption patterns should also be addressed in line with SDG 10 (Reduced Inequality). Achieving this requires a synergistic approach that

integrates multiple strategies [46,72]. This study goes beyond conventional scenario modeling [49] by innovatively constructing an integrated assessment model that incorporates various strategies into the food system supply chain. This model quantifies the mitigation effects of different combined-action strategies across production, consumption, and supply chains, while also examining the synergies and trade-offs related to both carbon emissions and societal inequalities. Our modeling simulations highlight that a set of integrated strategies across the food system supply chain can enhance mitigation potential by up to 19.9%, suggesting that the previous integrated mitigation effect was underestimated. Moreover, this study achieves sustainable synergy between natural (emission reduction) and social (equity and health) coupled systems through integrating comprehensive strategies that encompass the entire life cycle of food systems.

A comprehensive integration of all recommended measures, particularly those aligned with the EAT-Lancet dietary guidelines, has the potential to reduce GHG emissions by 41.7%. These findings suggest that achieving the ambitious emission reduction target for limiting warming to 1.5 °C requires coordinated actions across multiple sectors, with a focus on addressing regional disparities. While our simulation results reveal strategy trade-offs between emission reduction and regional equity, the theoretical mechanisms behind these interactions require further explanation. Specifically, we examine interconnected pathways across production, consumption, and supply chain stages (Fig. S6 online). First, decarbonization-health linkages emerge at the production level. Low-carbon agricultural practices reduce emissions but can create yield-nutrition trade-offs that may compromise food security [73]. In contrast, at the consumption level, plant-based dietary transitions exhibit 20%–30% lower carbon footprints while enhancing nutritional adequacy, demonstrating potential co-benefits [74]. Supply chain decarbonization introduces constraints on nutritious food accessibility through carbon-intensive processing and transportation bottlenecks. Second, decarbonization intersects with equity through technological disparities. On the production side, smallholder farmers face disproportionate barriers to low-carbon technology adoption, generating heterogeneous mitigation costs across farm scales [75]. Consumption-side mechanisms reveal that carbon pricing policies impose regressive burdens on low-income households [76], while supply chain inequities emerge from spatially uneven low-carbon infrastructure investments that particularly disadvantage rural communities. Third, health-equity interactions operate primarily through economic accessibility mechanisms, where nutrient-dense food price premiums exacerbate dietary inequalities across socioeconomic strata [77]. These interconnected mechanisms trigger cascading effects and complex feedback loops throughout food systems. Consequently, integrated policy frameworks are essential to simultaneously optimize climate, health, and equity outcomes.

In addition to inter-departmental coordination, spatial planning plays a pivotal role from the production side in reducing emissions through strategic land-use management. Spatial redistribution of agricultural production is a key land-based climate change mitigation measure [6,78], especially helping to reduce transportation emissions of food system [37]. The OPT scenario in this study, with its 5.7% mitigation potential, not only aligns with previous studies [4,79,80] but also incorporates future agro-climatic potential yields, available reserve of arable land, and regional water scarcity constraints. By optimizing the spatial distribution of land use and production structure, long-term stress in cropland supply can be significantly reduced. Amidst global uncertainty [7], a low-carbon approach can be achieved through strategic planning of crop relocations and the reclamation of currently unused land with low carbon production potential. This includes allocating demand-driven rice expansion to currently underutilized land in Northeast China

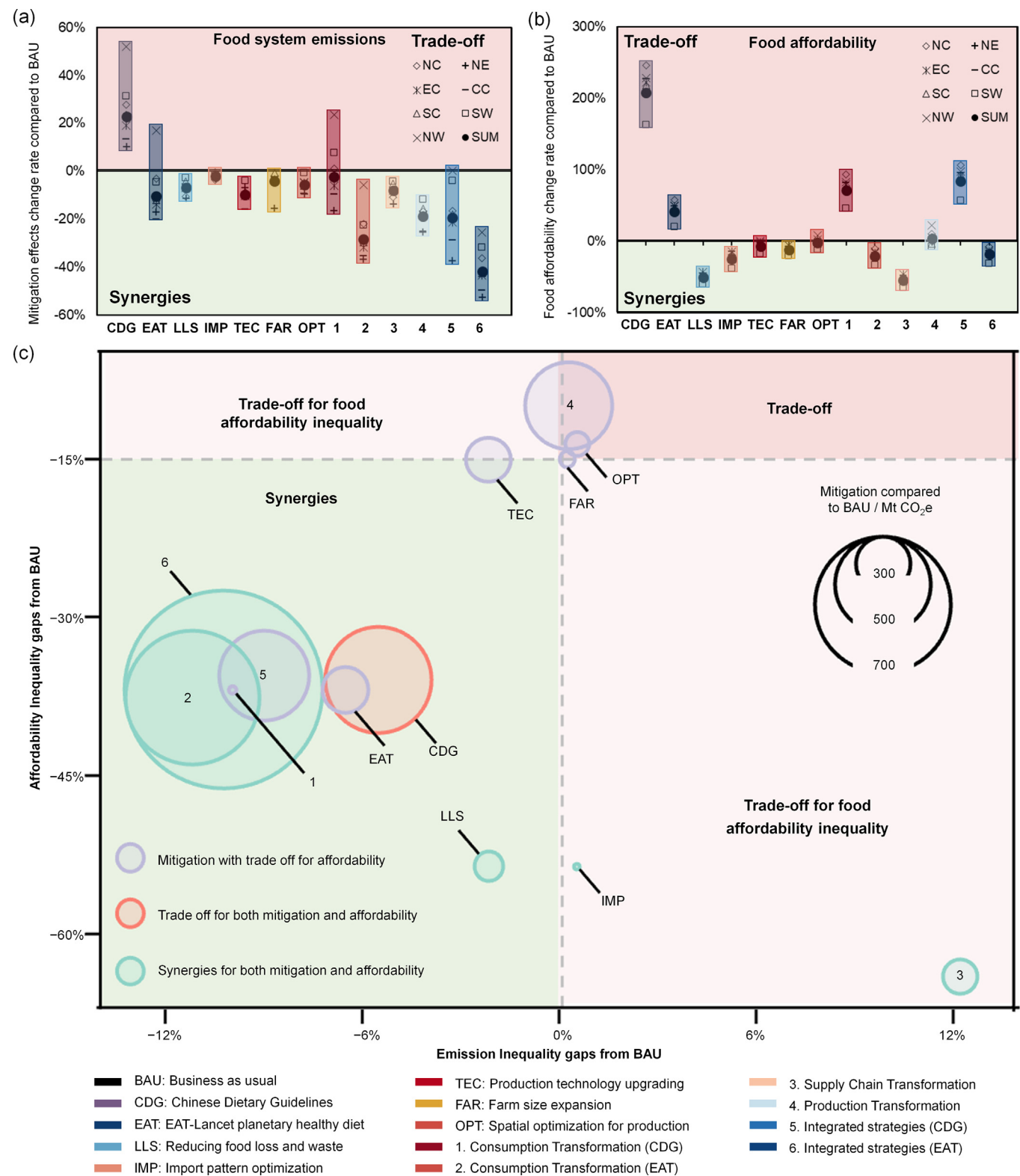


Fig. 5. Synergies and trade-offs of combined-action strategies for food system carbon emissions, food affordability and inequality. (a, b) Synergies and trade-offs for food system carbon emissions (a) and food affordability (b). Colored bars represent the impact of strategies on food system carbon emissions across different regions. Symbols are used to denote regional impacts, with the black bullet point representing the overall national impact. Shaded bars show the range of values between regions. Positive values with a pink background indicate trade-off effects relative to BAU, meaning increased emissions or decreased food affordability. Negative values with a green background imply synergies, where the strategies successfully reduce emissions or improve food affordability. (c) Synergies and trade-offs for inequality. The dark pink background in the first quadrant represents scenarios where trade-offs occur for both emissions and food affordability inequalities compared to the BAU scenario. Light pink backgrounds in the second and fourth quadrants indicate trade-offs in regional inequality in food affordability relative to the BAU scenario. Green background in the third quadrant represents strategies where reducing inequalities in both food affordability and emissions can be synergistic. The size of bubbles represents the relative changes in emissions by 2060 compared to the BAU scenario, while the color reflects the performance of each scenario in balancing synergies and trade-offs between emissions and food affordability (see Table 1 for description of strategies).

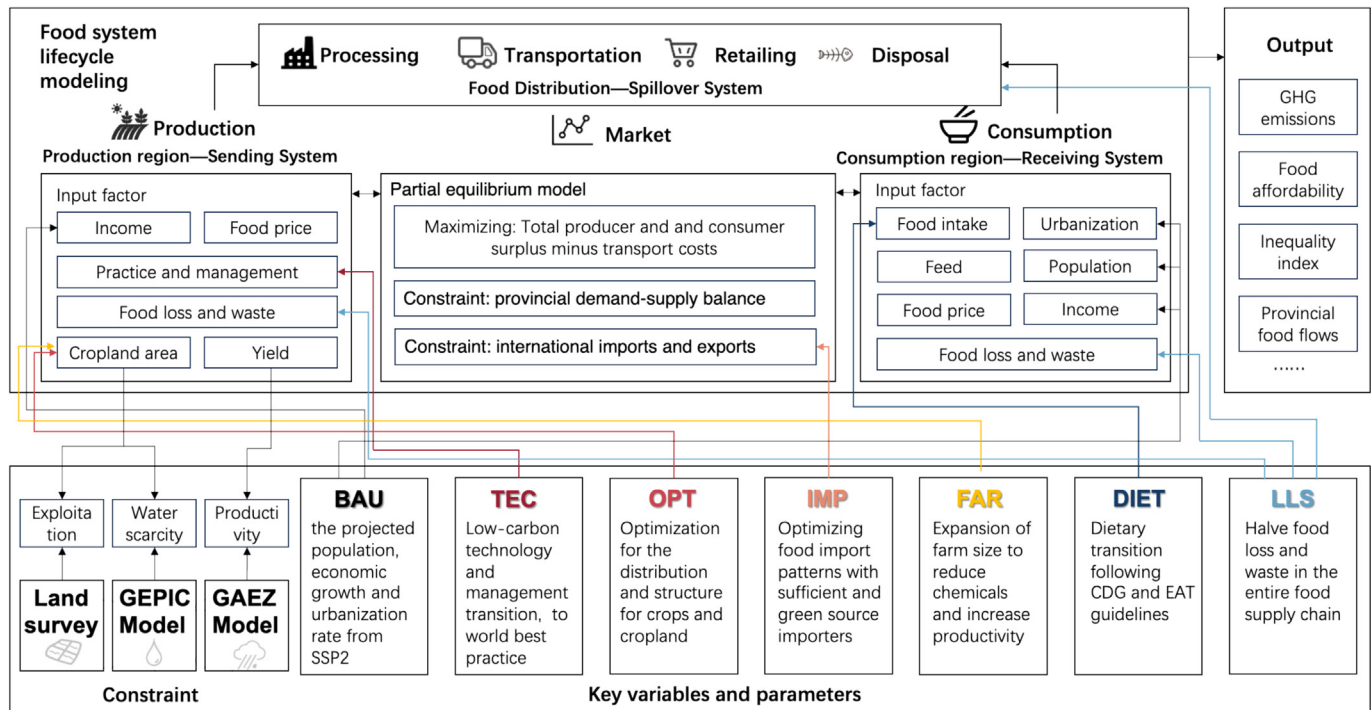


Fig. 6. Framework of the integrated assessment model for the food system in China. The Food System Lifecycle Integrated Assessment model (FSL-IAM) provides a comprehensive framework for achieving a sustainable transformation of the food system, focusing on low-carbon solutions, improved health outcomes, and reduced inequalities. By incorporating various strategies and their combinations, the model simulates the impacts on food system GHG emissions, food affordability, and resulting inequalities, which are measured using the Theil index. Production transformation strategies include technological upgrades in production (TEC), farm size expansion (FAR) and optimization of production space (OPT). Consumption transformation strategies involve dietary transitions following guideline (CDG) and (EAT), and halve food loss and waste (LLS). Supply chain transformation strategies include halve food loss and waste alongside the food supply chain (LLS) and import pattern optimization (IMP). The food lifecycle is connected through the food supply chain, where production is influenced by the availability of arable land reserves, regional water scarcity, and best attainable yields. Regional food is modeled using partial equilibrium, which is constrained by the balance between regional supply and demand.

and the Yangtze River Delta, potentially offsetting shortfalls in emission mitigation due to volatility in international markets. However, the implementation of the OPT strategy may involve regional trade-offs. For example, optimized production and land management policies could lead to cropland expansion in the North, Northeast, and Southwest China. Similarly, supply-side coordinated policies may drive up food costs in Northern and Eastern China. Consequently, this study advocates for a regionally coordinated mechanism to reduce food system emissions, ensuring that strategies are tailored to the specific needs and conditions of each region [81]. This specifically includes the need to establish a local green food supply system, while drawing on the EU's example of establishing a "Just Transition Fund" for the food system to compensate regions and sectors that suffer economic losses due to emissions reduction. While the IMP strategy aids China's national targets, it entails the risk of carbon leakage where emissions are merely displaced [82]. Thus, the net global environmental benefit depends strictly on the production efficiency of trading partners compared to domestic producers. To ensure genuine global mitigation, trade relationships must prioritize regions with lower carbon intensities.

Dietary shifts hold considerable potential for climate mitigation, though different dietary guidelines present distinct trade-offs [83]. This study compares the impact of combined-action strategies that integrate supply, demand, and supply chain options under either the CDG or the EAT dietary guidelines. The academic community generally believes that healthy diets reduce food affordability [16]. However, by comparing single-action adoption of the EAT with combined-action adoption of the EAT (Strategy 2), this study found that combined strategies can mitigate the negative externalities of food affordability associated with healthy

diets. This underscores the importance of implementing integrated measures. Nevertheless, the synergistic effects of integrated measures rely on the careful selection of specific actions to minimize trade-offs. By comparing two integrated strategies (Strategies 5 and 6), this study observed that although both involve the combination of all measures, the emission reduction effect of the CDG combination is slightly inferior and leads to a decrease in food affordability (Fig. 5). This comparison further highlights the necessity for China to transform its dietary structure and guidelines. However, large-scale dietary shifts are challenging due to economic, cultural, and regional access constraints [84–86]. To effectively contribute to global emission reduction targets, China must go beyond the current CDG guidelines. Firstly, the development of "healthy and sustainable" dietary guidelines that consider environmental impacts and regional dietary diversity is essential. Secondly, authorities should actively compile and promote traditional, health-focused, and sustainable Chinese cooking methods and recipes, many of which are inherently aligned with sustainability principles [87,88]. Thirdly, given the synergistic effects of combined mitigation strategies on both production and consumption identified in this study, subsidies for low carbon, healthy food production could be implemented [89] and conveyed to consumers through carbon labeling [90]. These strategies not only help meet emission targets but also align with global efforts towards sustainable food systems.

A pressing concern is that global GHG emissions from the food system are on track to exceed the budget allocated for the 1.5 °C warming target, especially as global per capita caloric consumption shifts towards healthier levels [2]. According to existing scenarios, food consumption alone could surpass the emission budget for the 1.5 °C target. Furthermore, the expected rise in demand for animal

products could lead to even higher warming impacts from food consumption than currently projected [22]. Drawing on previous research [2], this study sets emission targets for both food and non-food sources, aiming to maintain global per capita control of warming. Our findings indicate that to meet the ambitious 1.5 °C target while achieving healthy diet intake, China must vigorously coordinate all measures to reduce GHG emissions from its food system. However, this ambitious strategy could also reduce regional social inequalities.

As with most studies, this research has several limitations. Firstly, the emissions inventory parameters for the processing, wholesale and retail stages primarily relied on the ESU World Food LCA Database (<https://esu-services.ch/data/fooddata/>). These post-production emission factors are available only at the national level and lack regional differences. The emission factor for cooking was adopted from UK food consumption survey data [91] and adjusted based on China's energy emission factors. This may lead to a higher proportion of emissions from retailing and cooking. Despite considering parameters for different foods, regions and time series, spatially uniform parameters were still adopted in some stages due to the lack of available data. This indicates that more work is needed to establish China's own food system GHG emission factors. Secondly, due to limited data, the packaging stage was excluded from this study, which accounted for 19.7% of China's food system emission according to the estimation of EDGAR_FOOD [44]. Including this stage would enhance comparability. In addition, while only 12 food types were considered, they account for 85.4% of the total calories and 88.7% of the protein intake in China. Thirdly, the modeling in this study was conducted at the provincial level. This scale allows for comprehensive national coverage and policy-relevant insights at the administrative level where many decisions are made. However, sub-provincial hotspots of environmental burden or social inequality may be obscured by provincial averages, potentially underestimating the magnitude of sustainability challenges in specific localities. Future research should prioritize finer-scale analyses, potentially at the prefecture or county level, to better capture spatial heterogeneity and provide more targeted policy guidance.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

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Author contributions

Xinxian Qi, Xianjin Huang, Kuishuang Feng, and Laixiang Sun conceptualized the study and designed the research. Xinxian Qi and Zemiao Liu developed and performed simulations of food system lifecycle integrated assessment model (FSLIAM). Honglin Zhong performed the GAEZ model. Pan He, Hong Yang, Julian R. Thompson, Taiyang Zhong, and Xiao Lyu conducted the investigation. Xinxian Qi, Yiqi Zhou, and Yanfeng Di created the visualizations. Xianjin Huang, Kuishuang Feng, Laixiang Sun, and Hong Yang supervised the project. Xinxian Qi wrote the original draft, while Pan He, Hong Yang, Julian R. Thompson, Taiyang Zhong, and Xiao Lyu reviewed and edited the manuscript.

Data availability

All data needed to evaluate the conclusions in the paper are present in the paper and/or the [Supplementary datasets S1–S3](#). The GAMS code used for this analysis are available on Zenodo at <https://doi.org/10.5281/zenodo.18771927>. Additional data related to this paper may be requested from the authors.

Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scib.2026.02.018>.

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