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## Title page

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

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# 1 Summary

2 标题：协同低碳、健康和公平的中国食物系统综合减碳路径

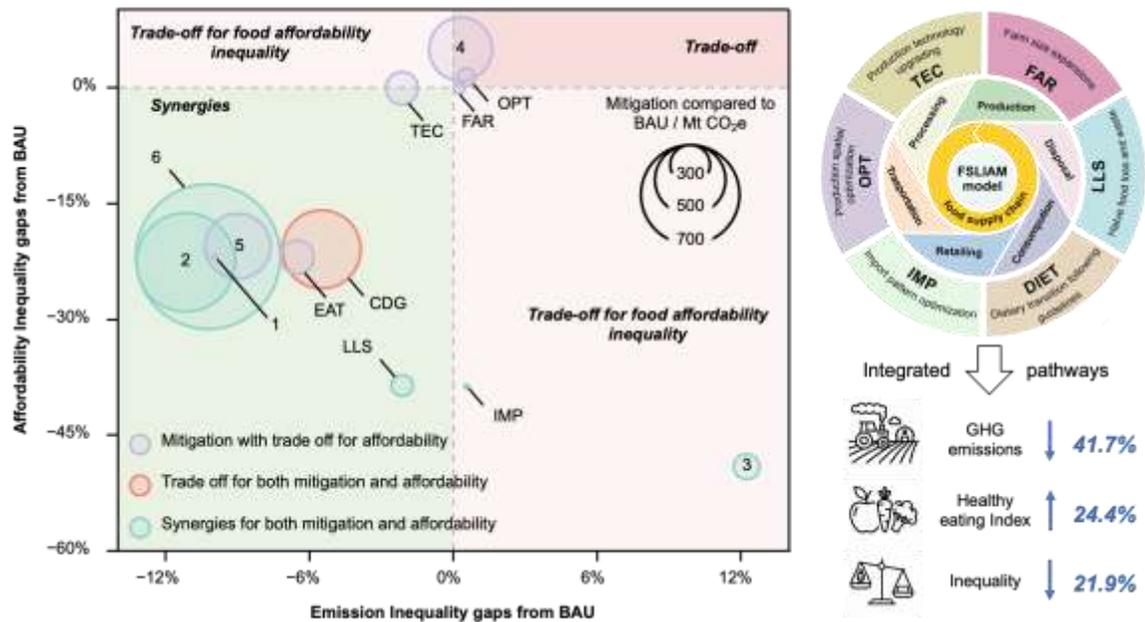
3 作者：漆信贤，刘泽淼，周仪琪，钟洪麟，何盼，黄贤金，孙来祥，冯奎双，杨洪，Julian R. Thompson，  
4 邸彦峰，钟太洋，吕晓

5 关键词：食物系统转型；碳减排；综合策略；权衡和协同效应

6 摘要：为了实现食物系统碳减排目标的同时协同健康和公平，本研究基于中国省级食物系统自下而上  
7 上生命周期评估框架，构建区域食物系统综合评估模型。实施单一减缓策略可能会增加食物成本，  
8 加剧不平等且无法实现碳减排目标。通过整合供应链、消费转型和土地管理等综合策略，可在2060  
9 年将食物系统温室气体排放减少41.7%，健康膳食指数提高24.4%，并将不平等减少21.9%。研究强  
10 调需要构建跨部门和区域协调的食物系统框架来实现气候目标并实现营养和公平的协同。

11

# 12 Graphic abstract



13

## 14 **Abstract**

15 Tackling the ongoing challenges of food insecurity and nutritional deficiencies may  
16 complicate efforts to reduce carbon emissions within the food system, a critical component  
17 of meeting the climate target. Spatial disparities in food distribution further intensify  
18 existing inequalities. This study enhances a widely used regional integrated assessment  
19 model by incorporating a novel bottom-up lifecycle assessment framework for China's  
20 food system at the provincial level. It evaluates trade-offs and explores synergies across  
21 strategies aimed at balancing healthy diets, low carbon emissions, and reduced inequalities  
22 through 2060. The results indicate that implementing single mitigation measures may  
23 increase food costs and exacerbate inequality without achieving the target carbon emission  
24 mitigation goal. However, a coordinated approach integrating actions across the supply  
25 chain, consumer demand, and land management transformation could reduce greenhouse  
26 gas emissions by 41.7%, improve nutritional quality by 24.4%, and decrease inequality by  
27 21.9% by 2060. This study highlights the need for a cross-sectoral and regionally  
28 coordinated food system framework to achieve the climate target, ensure adequate nutrition,  
29 and foster an affordable, equitable food system.

30 **Keywords:** food system transformation, carbon emission, inequality, integrated strategy,  
31 trade-offs and synergies

## 32 **1. Introduction**

33  
34 The ongoing challenges of food insecurity and nutritional deficiencies, which affect  
35 about 9.1% of the global population [1], could complicate efforts to reduce carbon  
36 emissions within the food system, a critical step toward meeting the 1.5°C target [2, 3].  
37 Production-side interventions, such as planting pattern optimization and innovative  
38 management, can mitigate carbon emissions and environmental impacts [4, 5], improving  
39 farmers' welfare [6], while supply-side strategies should closely align with the growing  
40 food demand [7]. On the consumption side, dietary transitions are identified as having the  
41 highest potential for emission mitigation [8-11]. However, most national dietary guidelines  
42 primarily focus on health, with only a few guidelines mentioning environmental  
43 sustainability recommendations [12-15], leading to conflicts between improving nutrition  
44 and reducing carbon emissions [15-17]. For example, adhering to the EAT-Lancet  
45 recommendations aimed at improving planetary and human health could reduce food  
46 affordability due to inadequate supplies of healthy food [18, 19]. In China, following the  
47 Chinese Dietary Guidelines (CDG) could even increase emissions by 2.5 Gt CO<sub>2e</sub> per year,  
48 a 7.5% rise from the baseline [16, 20]. Therefore, beyond isolated actions on food  
49 production or consumption, integrated and holistic strategies are necessary to achieve both  
50 low-carbon and health co-benefits within the food system [21-24].

51 Food systems, understood as coupled human–natural systems [25], exhibit cross-scale  
52 feedbacks between biophysical processes and societal dynamics within the sustainability  
53 science perspective [26]. Across the entire lifecycle, the food system integrates a spatial  
54 nexus linking production landscapes, interregional supply chains, consumption patterns,  
55 and their associated environmental outcomes and social well-being [27]. While regional  
56 distribution disparities within the food system, driven by the spatial heterogeneity of  
57 natural resource endowments, further complicate the efforts to achieve environmental and  
58 social sustainability [28-30]. Production-intensive regions, often focused on food exports,  
59 bear a disproportionate share of emissions resulting from carbon-intensive consumption

60 patterns in food-importing regions [31, 32]. This imbalance undermines both  
61 environmental sustainability and social well-being [33, 34] at international and sub-  
62 national levels [35, 36]. In China, food system distribution disparities are exacerbated by  
63 market-driven supply and demand dynamics, with cropland displacement [37] within the  
64 national food system further intensifying these challenges [35]. As shifts in supply and  
65 demand deepen regional disparities [38, 39], coordinated approaches are essential to  
66 integrate the supply and demand sides of the food supply chain [40], particularly to address  
67 the inequalities caused by shifting food distribution patterns. Health, sustainability, and  
68 justice are the transformation goals for the planetary food systems [41]. So far, efforts to  
69 achieve co-benefits often overlook inequality issues [42, 43], and it remains unclear  
70 whether integrated strategies aimed at both climate mitigation and health improvement can  
71 effectively address inequalities.

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

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

## 96 **2. Materials and Methods**

### 97 **2.1 System boundary of the China's food system**

98 The assessment of China's food system ([Text S1](#) online for the definition of the food  
99 system) includes 12 primary food categories commonly consumed by Chinese population.  
100 These categories consist of five plant-sourced foods (rice, wheat, maize, vegetables, and  
101 fruit), six animal-sourced foods (pork, beef, mutton, poultry, egg, and milk), and an  
102 aggregate category for aquatic food, which includes fish, shrimp, crab, shellfish, and algae.  
103 Together, these 12 food categories provide 85.4% of the total calory intake and 88.7% of  
104 the total protein intake for the Chinese population [51]. In line with the EU's (2020) Farm-  
105 to-Fork Strategy [52], the food supply chain in this study is divided into three key stages:

106 pre-production (extraction of the resources needed to produce agricultural products),  
107 production (land and farm management practices during food production processes), and  
108 post-production (processing, transportation, packaging, distribution, retail, household  
109 refrigeration and cooking) (Figs. S1 and S2 online). The carbon emissions from food loss  
110 and waste throughout the entire food supply chain were estimated using loss and waste  
111 ratios and the accounting methods developed by Xue et al [53] and Niu et al. [54]. The  
112 accounting results show a good consistency with the existing food system emission  
113 accounting results (Table S1 and Table S2).

## 114 **2.2 Integrated assessment model of China's food system lifecycle**

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

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

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

149 (2) Inter-Provincial and International Trade. In addition to achieving equilibrium on  
150 provincial markets, the model simulates inter-provincial and international trade. The model  
151 includes 31 regions and 12 food categories. A net social revenue (NSR) maximization

152 module was added to estimate the total import and export of each food type for each  
 153 province [58]. This module considers the transportation costs between regions and  
 154 maximizes the producer and consumer surpluses while minimizing the cost of transporting  
 155 products across regions.

156 Objective function:

$$157 \quad \text{Max } (NSR = \sum_{i=1}^N MIQ_i * P_i - \sum_{j=1}^{31-N} MOQ_j * P_j - \sum_{i=1}^N \sum_{j=1}^{31-N} c_{i,j} * z_{i,j}) \quad (1)$$

158 Subject to the following constraints:  
 159  
 160

$$\sum_{i=1}^N z_{i,j} \geq MIQ_j \quad (2)$$

$$\sum_{j=1}^{31-N} z_{i,j} \leq MOQ_i \quad (3)$$

$$(z_{i,j}, MIQ_i, MOQ_j) \geq 0 \quad (4)$$

161 where  $MIQ_i$  is the food shortage in the region  $i$  ( $1*31$ ),  $MOQ_j$  is the food surplus in the  
 162 region  $j$  ( $1*31$ ),  $i$  is the food shortage region,  $j$  is the food surplus region,  $N$  is the total  
 163 number of shortage provinces,  $z_{i,j}$  is the sale ( $31 * 31$ ) from food surplus area  $j$  to grain  
 164 shortage area  $i$ ,  $P_i$  is the food price in the region  $i$  ( $1 * 31$ ),  $P_j$  is the food price in the  
 165 region  $j$  ( $1 * 31$ ), and  $c_{i,j}$  is the food transportation cost from provinces  $i$  to  $j$ . Based on  
 166 the *National Social Food Supply and Demand Balance Survey Table in 2018* obtained from  
 167 the National Food and Strategic Reserves Administration, this study also adjusted the  
 168 model to ensure that the inter-regional food trade matrix from model's operation matches  
 169 the quantities of food inflows and outflows in 2018 for each type of food at the provincial  
 170 level.  
 171

172 (3) Scenario-Based Optimization. The scenario-based optimization objective  
 173 function aims to minimize total food system GHG emissions across the entire lifecycle of  
 174 12 food types and 31 regions towards 2060, while taking into account constrains such as  
 175 reserve arable land, agro-climatic yield potential, and regional water scarcity. The model  
 176 incorporates various scenario settings (Fig. 6), including exogenous variables such as  
 177 dietary patterns (used in the CDG and the EAT scenarios), farm size, food loss and waste  
 178 ratios, international imports and exports, land reclamation, and production emission  
 179 intensities (Text S5 for more details)

180 The model outputs include lifecycle emissions of the entire food supply chain, food  
 181 affordability, and cropland expansion projections. Food affordability is defined as the share  
 182 of total food expenditure in total income. Food consumption expenditure is calculated as  
 183 the product of food prices and food consumption quantities, which are outputs of the model  
 184 and considered endogenous variables, while income is derived from SSP outputs [59] and  
 185 is exogenous to the model. As a scenario-based integrated assessment model, it internalizes  
 186 economic and social outputs from the SSP framework to form a long-term dynamic

187 evaluation for 2060. The model is executed in the General Algebraic Modeling System  
188 (GAMS), a high-level platform for mathematical optimization.

189 The business as usual (BAU) scenario follows the Shared Socioeconomic Pathway 2  
190 (SSP2), which is regarded as mostly aligning with the current development trends in  
191 population, economy, technology, and resource use [60, 61]. Under SSP2, China is  
192 expected to gradually reduce its dependence on fossil fuels, with its population peaking at  
193 1.4 billion around 2035 and urbanization reaching 80% by 2050. The population in 2060  
194 is projected to be 1.36 billion. This study revised the population data of SSP2 based on  
195 China's seventh population census conducted in 2020. All other single action scenarios in  
196 this study use the BAU (SSP2) as the reference.

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

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

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

225 The Imports (IMP) scenario explores the potential for increasing food imports to  
226 mitigate GHG emissions within China's food system. According to projections from  
227 [OECD-FAO \(https://stats.oecd.org/index.aspx?queryid=71240\)](https://stats.oecd.org/index.aspx?queryid=71240), China's imports of  
228 livestock, poultry, meat and dairy products are expected to increase, with livestock and  
229 poultry food imports rising by 24.8% and dairy imports by 27.7% by 2025 compared to  
230 2018. This study extends the OECD-FAO trend projections from 2025 to 2060, with future  
231 imports constrained by the supply capacities of potential exporter partner ([Table S6](#)).

232 The Farm Size Expansion (FAR) scenario considers the relationship between farm  
233 size and the application of pesticides and fertilizers. Empirical studies show that larger  
234 farms tend to use fewer chemical inputs per hectare, which in turn reduces GHG emissions  
235 [66]. This scenario calculates changes in pesticide and fertilizer use based on projected  
236 increase in average household farm size and estimates the resulting emissions reductions.

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

### 243 **2.3 Nutritional Quality Evaluation by Alternative Healthy Eating Index (AHEI)**

244 The Alternative Healthy Eating Index (AHEI) is a widely used dietary quality  
245 assessment indicator developed by Harvard T.H. Chan School of Public Health, aim to  
246 evaluate the quality of diets, and has been updated periodically to reflect the latest scientific  
247 evidence on diet -health relationships [67]. It comprises two component categories. (1)  
248 Adequacy Components promote beneficial elements, including vegetables, fruits, whole  
249 grains, nuts and legumes, long-chain omega-3 fatty acids, and Polyunsaturated Fatty Acids  
250 (PUFAs). Higher intake of these components results in higher scores. (2) Moderation  
251 Components should be consumed in limited quantities., including red and processed meats,  
252 sugary beverages, sodium, alcohol. Lower intake of these components results in higher  
253 scores. Each component is scored from 0 to 10 with intermediate intake levels scored  
254 proportionally. Since beverages and alcohol were excluded from this study’s food system  
255 boundaries, with the total possible score ranging from 0 to 90. Higher scores indicating  
256 better dietary quality aligned with recommendations. The AHEI uses density, intake per  
257 1,000 kcal, making it adaptable across different energy needs without adjustments for age,  
258 sex, or physical activity. This approach normalizes intake relative to total energy  
259 consumption, ensuring comparability across diverse populations.

### 260 **2.4 Theil index for regional inequality assessment**

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

271

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

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

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

272 where  $T$  denotes the total Theil index;  $T_w$  and  $T_b$  are the Theil indices for within-  
 273 region and between-region inequalities, respectively;  $i$  and  $j$  refer to the province  $i$  in  
 274 the region  $j$ ;  $y_i$  represents the impact including emissions, cropland expansion, or food  
 275 expenditures of the province  $i$ ;  $\bar{y}$  is the mean impacts. The Theil index can be decomposed  
 276 into within-group and between-group inequality components, making it particularly  
 277 valuable for understanding the sources of regional inequality. A Theil index value of 0  
 278 indicates perfect equality, while higher values signify greater inequality. This index's  
 279 sensitivity to changes in different segments of impacts distribution makes it an excellent  
 280 tool for evaluating the effectiveness of mitigation strategies aimed at reducing inequality.

## 281 2.5 Uncertainty

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

290 To assess uncertainty, empirical distribution functions were established for activity  
 291 and emission factors, and appropriate probability density function models were selected.  
 292 The Monte Carlo method was used to calculate the established probability density function  
 293 1,000 times, determining the 95% CI range for each food type in different stages (Text S7).  
 294 Following IPCC Guidelines [70], uncertainties were combined and transmitted through  
 295 two types of methods, applicable to merging unrelated or related emission sources, as  
 296 specified in Eqs. (8) and (9):

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

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

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

299

## 300 2.6 Data Source

301 This study compiles comprehensive datasets for China's food system lifecycle analysis  
 302 across 31 provinces, categorized into three main components (Table S2). (1) Parameters  
 303 for China's food system lifecycle. Socioeconomic parameters including per capita GDP,  
 304 urbanization rates, and Consumer Price Index were sourced from national and provincial  
 305 statistical yearbooks. Food prices from China Price Yearbooks enabled monetary-to-  
 306 physical quantity conversions. Lifecycle emission parameters were derived from IPCC  
 307 2006 National GHG Inventory Guidelines, China's Provincial GHG Inventory Compilation  
 308 Guide 2011, and peer-reviewed literature. Electricity emission factors utilized regional

309 power grid baselines from the National Development and Reform Commission (Data S1).  
310 (2) Emission factors of China's food system lifecycle. Regional and food-type-specific  
311 emission factors were calculated using production data from national agricultural cost-  
312 benefit surveys, covering fertilizer application rates, seed usage, pesticide dosages, fuel  
313 consumption, and production coefficients (Data S2). (3) Activity data of China's food  
314 system lifecycle encompass production and consumption statistics for 12 food types from  
315 China Statistical Yearbooks and provincial yearbooks (Data S3).. Data processing involved  
316 disaggregating aggregated consumption categories using regional consumption patterns  
317 (Text S8) .

318

### 319 **3. Results**

#### 320 **3.1 Existing inequalities and gaps of GHG emissions and dietary quality in China's** 321 **food system**

322 Over the past three decades (1990-2023), China's food system transformation has not  
323 only led to a 19.0% improvement in residential dietary quality, as measured by the AHEI,  
324 but also a significant 115.2% rise in GHG emissions. The GHG emissions from the full  
325 lifecycle of China's food system increased from 0.94 ( $\pm 0.36$ ) Gt CO<sub>2e</sub> a<sup>-1</sup> in 1990 (CO<sub>2</sub>  
326 equivalent, GHGs were converted into CO<sub>2</sub> equivalent according to the 100-year Global  
327 Warming Potential, as specified in IPCC AR5, with 95% confidence interval in the  
328 parentheses) to 2.03 ( $\pm 0.77$ ) Gt CO<sub>2e</sub> a<sup>-1</sup> in 2023 (Fig. 1a; and Table S7 for a detailed  
329 discussion on the uncertainty). The increase in emissions is primarily attributed to the  
330 consumption of carbon-intensive animal-based food, which accounted for 56.3% in 2023,  
331 as well as the rapid development of the supply chain in the post-production stage, which  
332 accounted for 43.0% in 2023 (Fig. 1c). Meanwhile, the AHEI has risen from 53.6 scores  
333 (out of a total of 90 scores) in 1990 to 63.8 scores in 2023, mainly due to a 4.1-fold increase  
334 in the consumption of PUFA -rich aquatic food and a 4.6-fold increase in fruit consumption  
335 (Fig. 1b). China's rapid urbanization has intensified food system mitigation pressures, with  
336 urban food system carbon emissions escalating from 0.26 Gt CO<sub>2e</sub> a<sup>-1</sup> in 1990 to 1.33 Gt  
337 CO<sub>2e</sub> a<sup>-1</sup> in 2023—a 4.2-fold increase that constitutes the primary driver of China's food  
338 system emissions growth (Fig. 1a). Concurrently, urbanization-induced improvements in  
339 dietary consumption patterns have yielded a substantial 32.1% enhancement in rural  
340 residents' AHEI scores between 1990-2023, while urban residents' dietary quality has  
341 remained largely stagnant since 2000 (Fig. 1b). These divergent trajectories underscore the  
342 urgent imperative for comprehensive structural transformation of China's food systems to  
343 achieve carbon mitigation and health co-benefits.

344 This food system transformation has also exacerbated regional inequalities, with GHG  
345 emissions from food systems rising significantly in both southern (112.8%) and northern  
346 (122.5%) parts of the country. Northwest China (NW) saw the highest emissions growth  
347 rate at 173.5%, largely driven by a 4.3-fold increase in meat-related emissions (Fig. 2a). In  
348 terms of the AHEI changes, Hebei in North China saw the most substantial improvement  
349 at 27.9 scores (90 scores in total) mainly due to increases in long-chain omega-3 and  
350 polyunsaturated fatty acids, while Qinghai in Northwest China exhibited the slowest  
351 growth of only 5.8 AHEI scores (Fig. 2b). Therefore, China faces trade-off in regions like  
352 Northwest China, where food-related carbon emissions have increased without  
353 corresponding adequate nutritional gains.

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

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

### 383 **3.2 Outcomes of single-action strategies for emission mitigation and healthy targets**

384 To address the trade-off between GHGs mitigation and nutrient improvements, five  
385 additional single-action strategies were developed alongside the BAU, CDG, and EAT (see  
386 Method; Text S5. and Table 1 for a description of each strategy). Using the enhanced  
387 FSLIAM (see Methods and Text S3 for the model framework), we projected GHG  
388 emissions and food affordability under these strategies through 2060. The BAU scenario  
389 serves as the reference. Under the BAU, food system emissions are projected to reach 2.39  
390 Gt CO<sub>2</sub>e a<sup>-1</sup> by 2060, a 17.5% increase from current levels (Fig. 3a), while food  
391 affordability improves by 16.6%, driven by income growth (Fig. 3b).

392 In the BAU scenario, the transition in dietary patterns is primarily driven by  
393 urbanization and rising income levels endogenous to SSP2, which have historically  
394 increased food demand and carbon emission in China since the early 1990s. A shift to the  
395 CDG diet could result in a 22.8% increase, with the 95% CI (1.5%, 39.9%), in emissions  
396 compared to the BAU, whereas the EAT diet could reduce emissions by 10.3%, with the  
397 95% CI (-20.9%, 7.9%) (Fig. 3a). However, these dietary transitions would negatively  
398 impact food affordability, with CDG and EAT leading to reductions of 208.3% and 41.4%,  
399 respectively, compared to the BAU (Fig. 3b). The sudden decline in affordability beginning

400 in 2020 reflects the immediate market response to dietary policy implementation, as  
401 increased demand for higher-value nutritious foods drives up average food prices.

402 The TEC scenario focuses on upgrading food production with advanced low-carbon  
403 technologies. We compare the carbon footprints of various food products between China  
404 and best-practice countries. For example, aligning with Australian mutton meat production  
405 standards could reduce carbon footprints by 3.2%. Overall, TEC offers a potential emission  
406 reduction of 9.9% ( $\pm 1.4\%$ ) for the total food system (Fig. 3a), with Central China exhibiting  
407 the highest reduction potential (15.9%) due to its substantially larger carbon footprint from  
408 rice cultivation (Fig. S4). Meanwhile, the benefit of green production technologies would  
409 improve food affordability by 7.4% through reducing the cost of production inputs (Fig.  
410 3b), with Southwest China facing increase at 17.1% (Fig. S5).

411 The FAR scenario links farm size expansion to reductions in pesticide and fertilizer  
412 use. Empirical studies show that a 1% increase in farm size is associated with a 0.3% and  
413 0.5% decrease in pesticide and fertilizer use<sup>[66]</sup>, respectively. Farm size is expected to grow  
414 under the BAU due to rural depopulation and land transfer. FAR could reduce carbon  
415 emissions by 4.1% ( $\pm 2.8\%$ ) (Fig. 3a), with Heilongjiang in Northeast China showing the  
416 greatest potential at 30.2% owing to significant expansion of farm size in this major grain  
417 production province (Fig. S4). However, the cost reduction from farm expansion could  
418 offset cross-regional supply costs, leading to an 11.6% improve in food affordability (Fig.  
419 3b).

420 The OPT scenario optimizes the spatial distribution of crop planting and cropland  
421 reclamation to minimize lifecycle food system carbon emissions without compromising  
422 the best attainable production levels in each province. This scenario accounts for  
423 constraints such as future agro-climatic potential yield (productivity) estimated by the  
424 GAEZ model under three RCP scenarios (Fig. 3e), exploitable reserves of arable land (area)  
425 from national land survey, and irrigation limitations without increasing regional water  
426 scarcity. The OPT scenario offers a potential GHG reduction of 5.7% ( $\pm 1.8\%$ ) (Fig. 3a),  
427 with the most significant reduction occurring in North, Central and Northwest China (Fig.  
428 3c and 3d). This low-carbon oriented optimization is achieved through strategic spatial  
429 planning of crop locations and the reclamation of low-emission, currently unused land. For  
430 example, rice production could be expanded into currently unexploited areas in Northeast  
431 China and the Yangtze River Delta, driven by demand consideration (Supplementary Fig.  
432 S4). However, redistribution cropland to regions with low-carbon production advantages  
433 is expected to decrease overall cross-regional supply costs through efficiency gains.,  
434 leading to an 1.8% improve in food affordability compared to the BAU scenario (Fig. 3b).  
435 However, for regions that rely on long-distance food supplies, such as the Northwest, the  
436 increase in cross-regional supply costs will worsen food affordability (Fig. S5).

437 The IMP scenario, based on the food import forecasts from OECD-FAO, explores the  
438 potential for increasing imports of livestock, poultry, meat, and dairy products to China.  
439 By selecting countries with low carbon emission intensities and sufficient export capacity  
440 (see Table S6 for potential exporter partners), the IMP scenario could mitigate GHG  
441 emissions by 12.3 Mt CO<sub>2e</sub> a<sup>-1</sup>. This includes 9.8 Mt CO<sub>2e</sub> from importing livestock and  
442 poultry and 2.5 Mt CO<sub>2e</sub> from importing milk, resulting in a total emissions reduction  
443 potential of 1.9% ( $\pm 1.7\%$ ) (Fig. 3a, Fig. S4). By alleviating domestic production pressure  
444 through increased imports, the IMP scenario also improves food affordability by 24.6%  
445 compared to the BAU (Fig. 3b). This improvement is especially pronounced in regions

446 with limited food supply capacity, such as Southwest China, where food affordability  
447 improved by 38.4%, especially Tibet, where it increases by 63.0% (Fig. S5).

448 The LLS scenario aligns with SDG 12.3, aiming to halve food loss and waste by 2030  
449 and continue reductions through 2060. LLS could reduce emissions by 6.8% ( $\pm 1.6\%$ ) by  
450 2060 (Fig. 3a), with Northeast and North China seeing the largest reductions at 11.3% and  
451 10.5%, respectively (Fig. S4). By narrowing the supply-demand gap, LLS would  
452 significantly improve food affordability by 50.5% (Fig. 3b), with the greatest improvement  
453 in Tibet, where affordability could rise by 75.3% (Fig. S5).

### 454 **3.3 Outcomes of combined-action strategies for climate target along the food supply** 455 **chain**

456 Fig. 4 compares the performances of all possible combined-action scenarios in  
457 mitigating GHG emissions from China's food system by 2060, targeting either a 1.5°C or  
458 2.0°C. As shown in Fig. 2c, a dietary shift to the CDG is projected to increase emissions  
459 by 22.8%, while adoption of the EAT diet could result in a 10.3% reduction in emissions.  
460 To achieve emissions reduction under the CDG scenario, at least two or more combined-  
461 action strategies are required. The most comprehensive scenario, which integrates all  
462 available measures, could achieve up to 19.3% reduction in GHG emissions with the CDG  
463 (Fig. 4a). In contrast, all combined-action strategies under the EAT diet show emission  
464 reduction potential, with the fully integrated scenario achieving a 41.7% reduction by 2060  
465 (Fig. 4b). Furthermore, to reveal how these combined-action scenarios contribute to the  
466 1.5°C or 2.0°C climate target, we categorize them across three transformational aspects:  
467 production, consumption, and supply chains (see Table 1 for a description of each  
468 combined-action strategy). To align with global climate goals, research suggests a 67%  
469 likelihood of meeting the 2.0°C target if cumulative emissions from food and non-food  
470 sources are capped at 1405 Gt CO<sub>2e</sub>, and 50% chance of achieving 1.5°C target if  
471 cumulative emissions are limited to 705 Gt CO<sub>2e</sub> by 2100 [2]. Distributing these carbon  
472 emission limits equally per capita, China's full contribution to the 2.0°C target would  
473 require controlling food and non-food emissions to 2.66 Gt a<sup>-1</sup> by 2060 (67% chance),  
474 while its full contribution to the 1.5°C target would necessitate limiting emissions to 1.34  
475 Gt a<sup>-1</sup> (50% chance). Under the BAU scenario, China's food system could contribute to  
476 achieving the 2.0°C target, though this also depends on emission reduction efforts from  
477 other sectors. However, the BAU emissions from China's food system alone would be  
478 insufficient to contribute to achieving the 1.5°C target, meaning that achieving alignment  
479 with the 1.5°C pathway requires at least a 43.8% reduction in food system emissions  
480 compared to the BAU scenario (Fig. 4c). This implies that China's food system emissions  
481 need significant reduction efforts to meet the 1.5°C target. Encouragingly, if all strategies  
482 are implemented alongside the EAT diet, a 41.0% emissions reduction could be attained,  
483 bringing China significantly closer to the 1.5°C target by 2060 (Fig. 4c). This finding  
484 highlights the critical role of integrating both demand - and supply-side measures to meet  
485 global climate goals.

486 An “enhancement effect” occurs when the combined actions in a strategy achieve a  
487 greater carbon emission reduction than the sum of the individual effects of each action.  
488 This additional emission reduction is achieved through lifecycle interactions within the  
489 food supply chain (Text S9 for formulas and details). The outermost light blue shading in  
490 Figs. 4a and 4b represents these enhancement effects. Approximately 71.9% of the  
491 combined action strategies exhibit such enhancement effects, leveraging synergies that

492 have previously been underestimated. In the scenario integrating all strategies under the  
493 CDG, a 13.5% enhancement effect is achieved. The greatest enhancement effect, 19.9%,  
494 results from the integration of supply chain and production transformation strategies (LLS,  
495 TEC, FAR, and IMP) (Fig. 4a).

### 496 **3.4 Synergies and trade-offs considering carbon emissions and societal inequalities**

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

507 Single-action strategies alone are insufficient to achieve synergies across carbon  
508 emissions mitigation, food affordability improvement, and inequality reduction. For  
509 example, while the CDG scenario results in a 22.8% increase in emissions, it also causes a  
510 drastic 208.3% decrease in food affordability due to the higher cost of healthy meals (Fig.  
511 5a and 5b). Although the EAT-Lancet scenario reduces emissions by 10.3% (Fig. 5a), it  
512 lowers affordability by 41.4% (Fig. 5b). On the supply chain side, the LLS strategy  
513 provides triple synergies by reducing emissions (-6.8%), substantially improving food  
514 affordability (-50.5%), and decreasing both environmental (-2.1%) and societal inequality  
515 (-38.7%). However, its mitigation potential is far from sufficient to meet the 1.5°C target  
516 (Fig. 4c). The IMP scenario achieves synergies between emissions reduction (-1.9%) and  
517 affordability improvement (-24.6%) but may exacerbate environmental inequality (+0.6%)  
518 due to its impact on domestic production (Fig. 5c). On the production side, the TEC  
519 scenario leads to a 7.4% improvement in food affordability due to abundant food supply  
520 and decreased food costs (Fig. 5b). The land-based strategy OPT, through expanding  
521 production in resource-rich regions, increases long-distance food supply, thereby raising  
522 costs and emissions and worsening regional environmental (+0.6%) and social inequalities  
523 (+1.3%) (Fig. 5c).

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

536

#### 537 **4. Discussion and conclusion**

538 Sustainable production and consumption, as advocated by SDG 12 (Responsible  
539 Consumption and Production) and the UN Food Systems Summit, are crucial for limiting  
540 GHG emissions within planetary boundaries [71]. However, the spatial heterogeneity  
541 amplified by agricultural intensification and shifting consumption patterns should also be  
542 addressed in line with SDG 10 (Reduced Inequality). Achieving this requires a synergistic  
543 approach that integrates multiple strategies [46, 72]. This study goes beyond conventional  
544 scenario modeling [49] by innovatively constructing an integrated assessment model that  
545 incorporates various strategies into the food system supply chain. This model quantifies  
546 the mitigation effects of different combined-action strategies across production,  
547 consumption, and supply chains, while also examining the synergies and trade-offs related  
548 to both carbon emissions and societal inequalities. Our modeling simulations highlight that  
549 a set of integrated strategies across the food system supply chain can enhance mitigation  
550 potential by up to 19.9%, suggesting that the previous integrated mitigation effect was  
551 underestimated. Moreover, this study achieves sustainable synergy between natural  
552 (emission reduction) and social (equity and health) coupled systems through integrating  
553 comprehensive strategies that encompass the entire life cycle of food systems.

554 A comprehensive integration of all recommended measures, particularly those aligned  
555 with the EAT-Lancet dietary guidelines, has the potential to reduce GHG emissions by  
556 41.7%. These findings suggest that achieving the ambitious emission reduction target for  
557 limiting warming to 1.5°C requires coordinated actions across multiple sectors, with a focus  
558 on addressing regional disparities. While our simulation results reveal strategy trade-offs  
559 between emission reduction and regional equity, the theoretical mechanisms behind these  
560 interactions require further explanation. Specifically, we examine interconnected pathways  
561 across production, consumption, and supply chain stages (Fig. S6). First, decarbonization-  
562 health linkages emerge at the production level. Low-carbon agricultural practices reduce  
563 emissions but can create yield-nutrition trade-offs that may compromise food security [73].  
564 In contrast, at the consumption level, plant-based dietary transitions exhibit 20-30% lower  
565 carbon footprints while enhancing nutritional adequacy, demonstrating potential co-  
566 benefits [74]. Supply chain decarbonization introduces constraints on nutritious food  
567 accessibility through carbon-intensive processing and transportation bottlenecks. Second,  
568 decarbonization intersects with equity through technological disparities. On the production  
569 side, smallholder farmers face disproportionate barriers to low-carbon technology adoption,  
570 generating heterogeneous mitigation costs across farm scales [75]. Consumption-side  
571 mechanisms reveal that carbon pricing policies impose regressive burdens on low-income  
572 households [76], while supply chain inequities emerge from spatially uneven low-carbon  
573 infrastructure investments that particularly disadvantage rural communities. Third, health-  
574 equity interactions operate primarily through economic accessibility mechanisms, where  
575 nutrient-dense food price premiums exacerbate dietary inequalities across socioeconomic  
576 strata [77]. These interconnected mechanisms trigger cascading effects and complex  
577 feedback loops throughout food systems. Consequently, integrated policy frameworks are  
578 essential to simultaneously optimize climate, health, and equity outcomes.

579 In addition to inter-departmental coordination, spatial planning plays a pivotal role  
580 from the production side in reducing emissions through strategic land-use management.  
581 Spatial redistribution of agricultural production is a key land-based climate change  
582 mitigation measure [6, 78], especially helping to reduce the transportation emissions of

583 food system [37]. The OPT scenario in this study, with its 5.7% mitigation potential, not  
584 only aligns with previous studies [4, 79, 80] but also incorporates future agro-climatic  
585 potential yields, available reserve of arable land, and regional water scarcity constraints.  
586 By optimizing the spatial distribution of land use and production structure, long-term stress  
587 in cropland supply can be significantly reduced. Amidst global uncertainty [7], a low-  
588 carbon approach can be achieved through strategic planning of crop relocations and the  
589 reclamation of currently unused land with low carbon production potential. This includes  
590 allocating demand-driven rice expansion to currently underutilized land in Northeast China  
591 and the Yangtze River Delta, potentially offsetting shortfalls in emission mitigation due to  
592 volatility in international markets. However, the implementation of the OPT strategy may  
593 involve regional trade-offs. For example, optimized production and land management  
594 policies could lead to cropland expansion in the North, Northeast, and Southwest China.  
595 Similarly, supply-side coordinated policies may drive up food costs in Northern and  
596 Eastern China. Consequently, this study advocates for a regionally coordinated mechanism  
597 to reduce food system emissions, ensuring that strategies are tailored to the specific needs  
598 and conditions of each region [81]. This specifically includes the need to establish a local  
599 green food supply system, while drawing on the EU's example of establishing a “Just  
600 Transition Fund” for the food system to compensate regions and sectors that suffer  
601 economic losses due to emissions reduction. While the IMP strategy aids China’s national  
602 targets, it entails the risk of carbon leakage where emissions are merely displaced [82].  
603 Thus, the net global environmental benefit depends strictly on the production efficiency of  
604 trading partners compared to domestic producers. To ensure genuine global mitigation,  
605 trade relationships must prioritize regions with lower carbon intensities.

606 Dietary shifts hold considerable potential for climate mitigation, though different  
607 dietary guidelines present distinct trade-offs [83]. This study compares the impact of  
608 combined-action strategies that integrate supply, demand, and supply chain options under  
609 either the CDG or the EAT dietary guidelines. The academic community generally believes  
610 that healthy diets reduce food affordability [16]. However, by comparing single-action  
611 adoption of the EAT with combined-action adoption of the EAT (Strategy 2), this study  
612 found that combined strategies can mitigate the negative externalities of food affordability  
613 associated with healthy diets. This underscores the importance of implementing integrated  
614 measures. Nevertheless, the synergistic effects of integrated measures rely on the careful  
615 selection of specific actions to minimize trade-offs. By comparing two integrated strategies  
616 (Strategies 5 and 6), this study observed that although both involve the combination of all  
617 measures, the emission reduction effect of the CDG combination is slightly inferior and  
618 leads to a decrease in food affordability (Fig. 5). This comparison further highlights the  
619 necessity for China to transform its dietary structure and guidelines. However, large-scale  
620 dietary shifts are challenging due to economic, cultural, and regional access constraints  
621 [84-86]. To effectively contribute to global emission reduction targets, China must go  
622 beyond the current CDG guidelines. Firstly, the development of “healthy and sustainable”  
623 dietary guidelines that consider environmental impacts and regional dietary diversity is  
624 essential. Secondly, authorities should actively compile and promote traditional, health-  
625 focused, and sustainable Chinese cooking methods and recipes, many of which are  
626 inherently aligned with sustainability principles [87, 88]. Thirdly, given the synergistic  
627 effects of combined mitigation strategies on both production and consumption identified  
628 in this study, subsidies for low-carbon, healthy food production could be implemented [89]

629 and conveyed to consumers through carbon labeling [90]. These strategies not only help  
630 meet emission targets but also align with global efforts towards sustainable food systems.

631 A pressing concern is that global GHG emissions from the food system are on track  
632 to exceed the budget allocated for the 1.5°C warming target, especially as global per capita  
633 caloric consumption shifts towards healthier levels [2]. According to existing scenarios,  
634 food consumption alone could surpass the emission budget for the 1.5°C target.  
635 Furthermore, the expected rise in demand for animal products could lead to even higher  
636 warming impacts from food consumption than currently projected [22]. Drawing on  
637 previous research [2], this study sets emission targets for both food and non-food sources,  
638 aiming to maintain global per capita control of warming. Our findings indicate that to meet  
639 the ambitious 1.5°C target while achieving healthy diet intake, China must vigorously  
640 coordinate all measures to reduce GHG emissions from its food system. However, this  
641 ambitious strategy could also reduce regional social inequalities.

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

664

#### 665 **Conflict of interest**

666 The authors declare that they have no conflict of interest.

667

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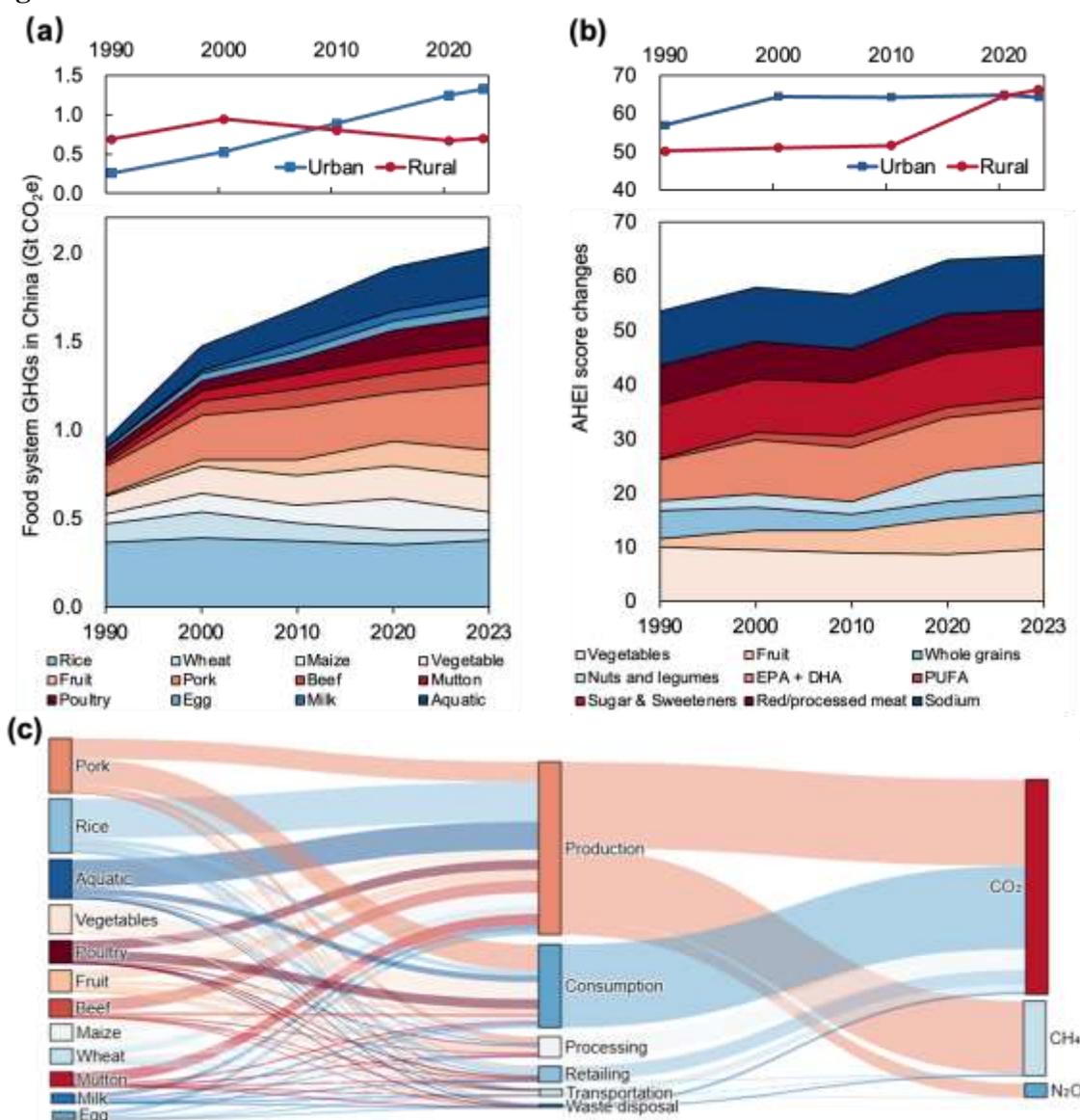
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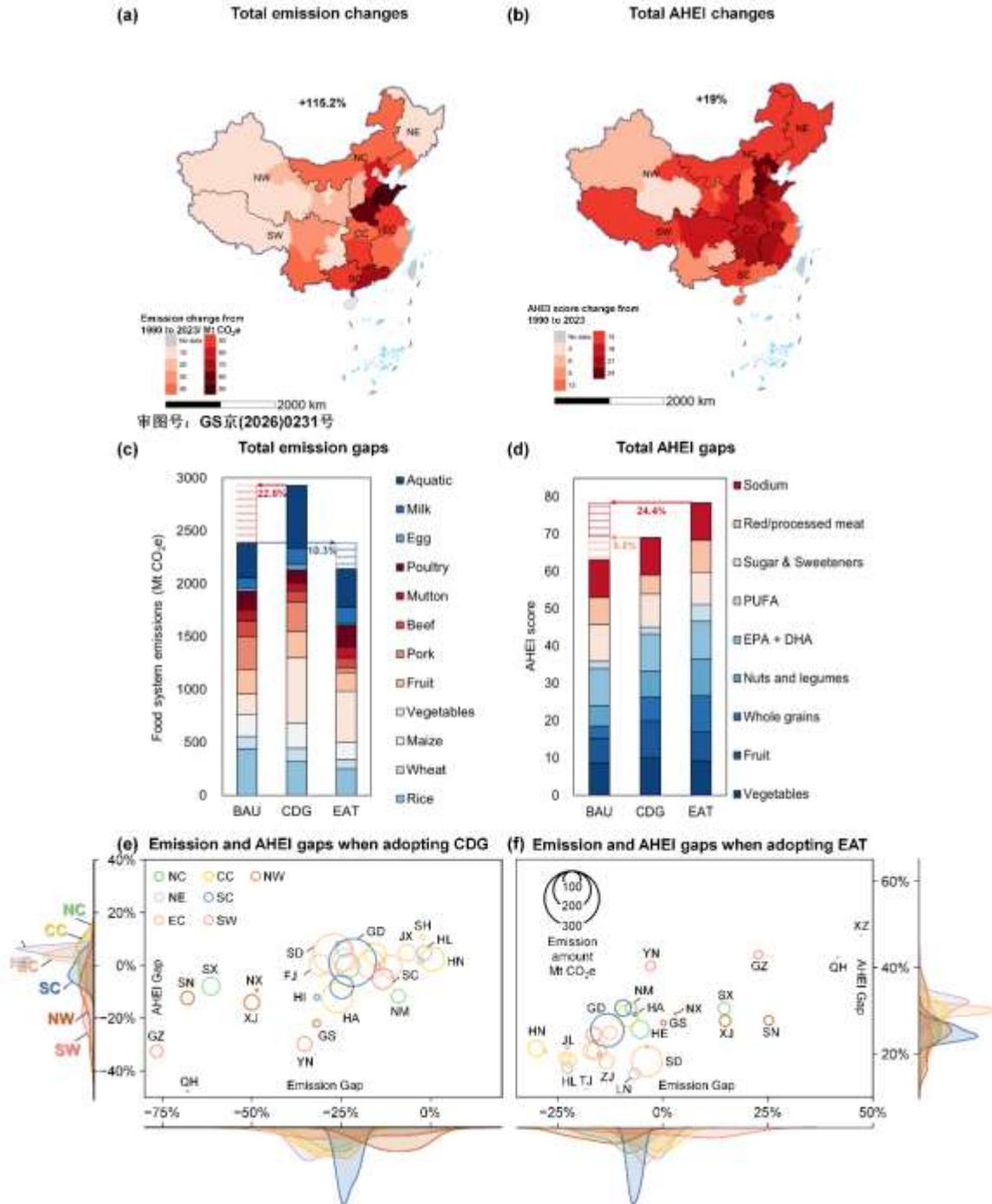
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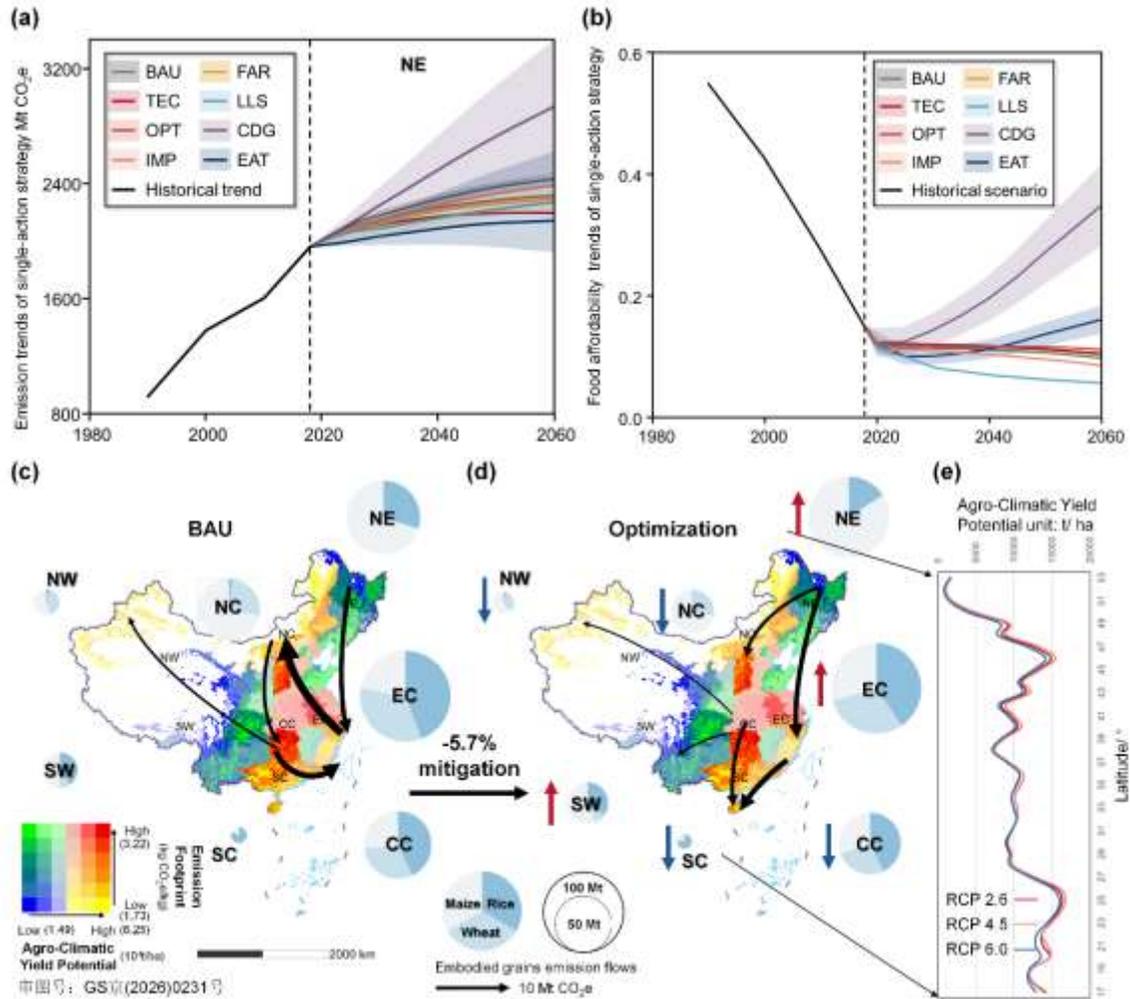
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 885 **Fig. 1. The lifecycle carbon emissions and AHEI trends of China’s food system. (a)**  
 886 **The pattern changes in China’s food system carbon emissions from 1990 to 2023. (b)**  
 887 **The pattern changes in the Alternative Healthy Eating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



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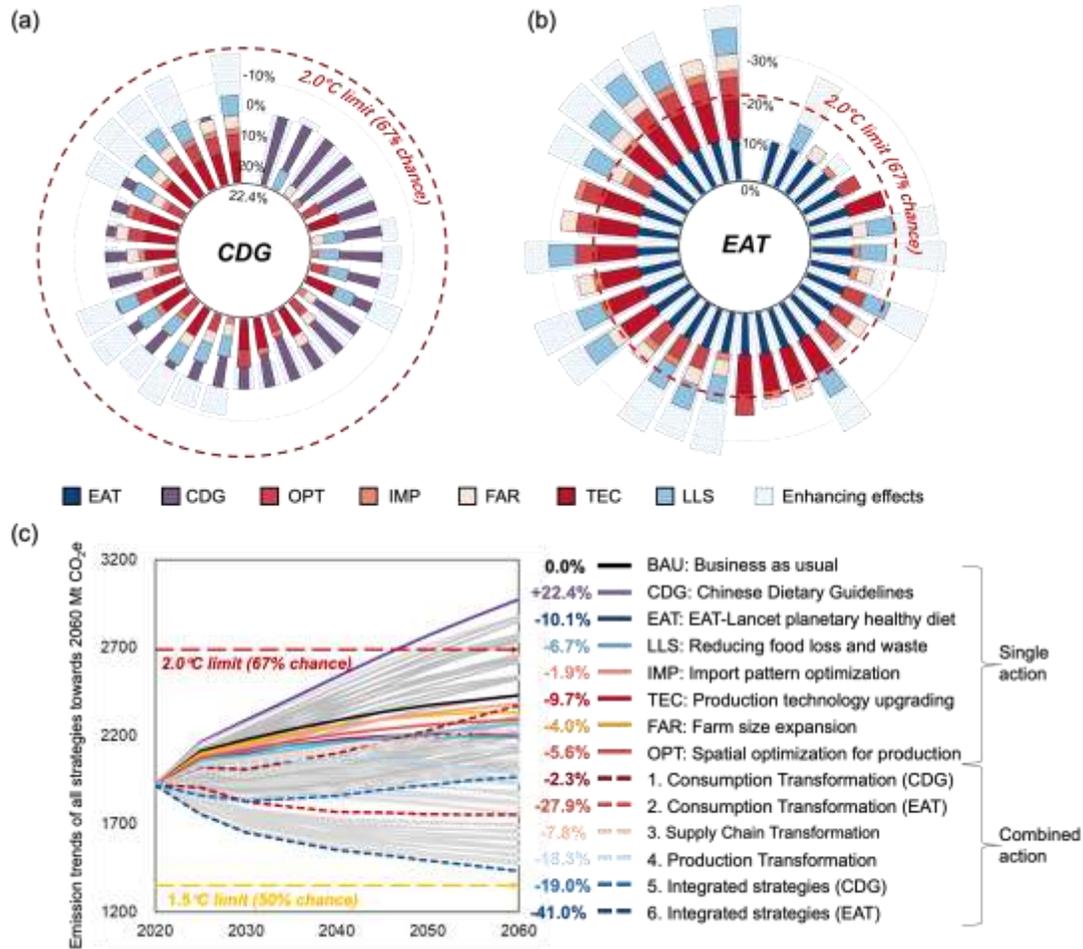
**Fig. 2. The carbon emission and AHEI patterns of China's food system.** (a) The distribution of changes in China's food system carbon emissions from 1990 to 2023, with regions categorized as Northeast China (NE), North China (NC), Northwest China (NW), East China (EC), South China (SC), Central China (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

900 and AHEI gaps when adopting CDG in 2060. The horizontal axis represents the emission  
901 gap, and the vertical axis represents the AHEI gap. Each circle represents a province, with  
902 the size of the circle indicating the province's emission levels when adopting CDG.  
903 Colored circles represent the regions to which the provinces belong. The curve below the  
904 horizontal axis shows the distribution density of all data points on the "Emissions Gap"  
905 dimension. The curve on the left or right side of the vertical axis shows the distribution  
906 density of all data points on the "AHEI Gap" dimension; **(f)** Regional emissions and AHEI  
907 gaps when adopting EAT in 2060, following the same structure as in E. The name of the  
908 circles as BJ = Beijing, TJ = Tianjin, HE = Hebei, SX = Shanxi, NM = Nei Mongol, LN  
909 = Liaoning, JL = Jilin, HL = Heilongjiang, SH = Shanghai, JS = Jiangsu, ZJ = Zhejiang,  
910 AH = Anhui, FJ = Fujian, JX = Jiangxi, SD = Shandong, HA = Henan, HB = Hubei, HN =  
911 Hunan, GD = Guangdong, GX = Guangxi, HI = Hainan, CQ = Chongqing, SC = Sichuan,  
912 GZ = Guizhou, YN = Yunnan, XZ = Xizang, SN = Shaanxi, GS = Gansu, QH = Qinghai,  
913 NX = Ningxia, XJ = Xinjiang

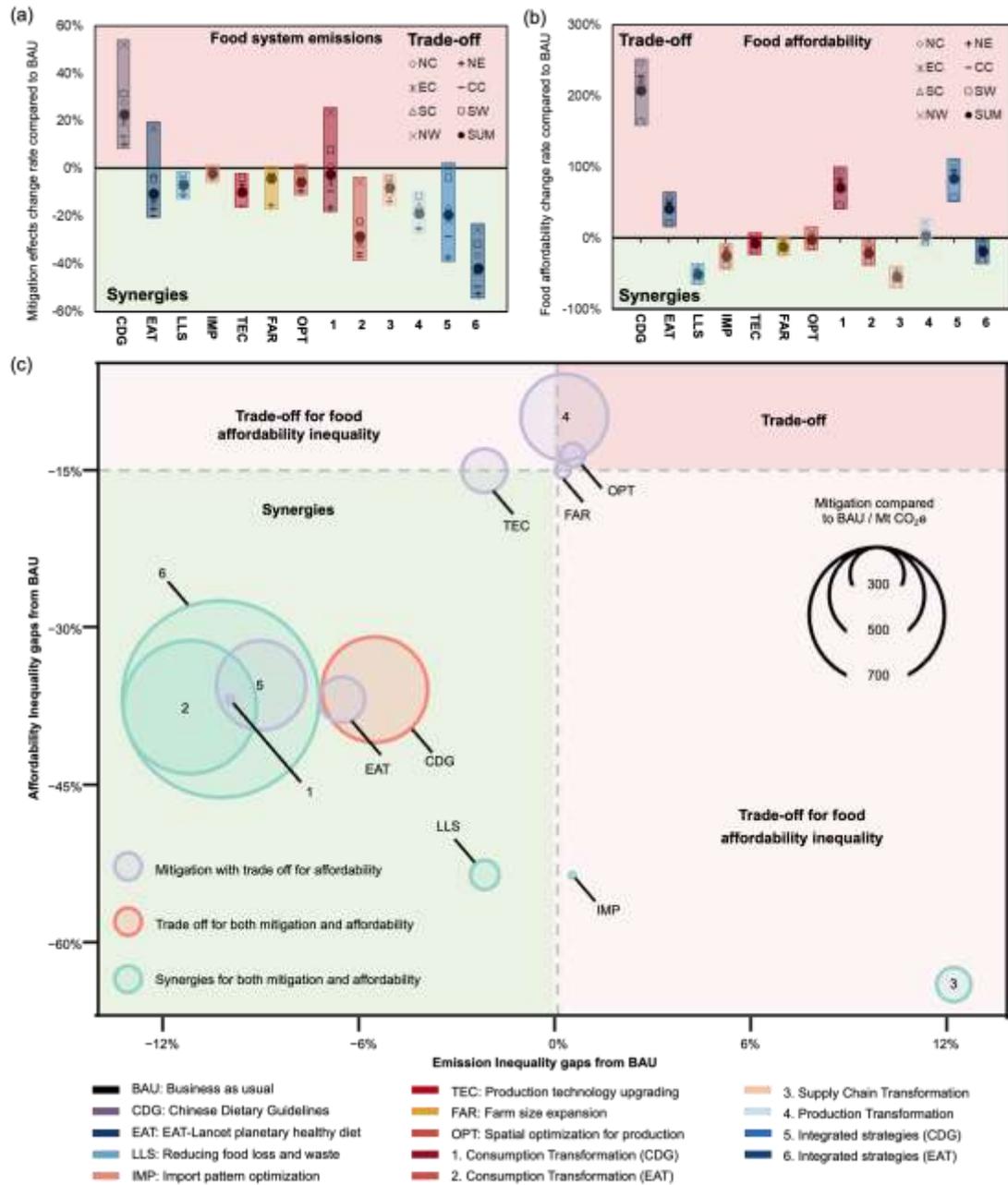


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915 **Fig. 3. Trends of carbon emission and food affordability in single-action pathways.**  
 916 (a) and (b) Historical and projected trends (2060) for food system GHG emissions (a) and  
 917 food affordability (b). Colored lines represent the trends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



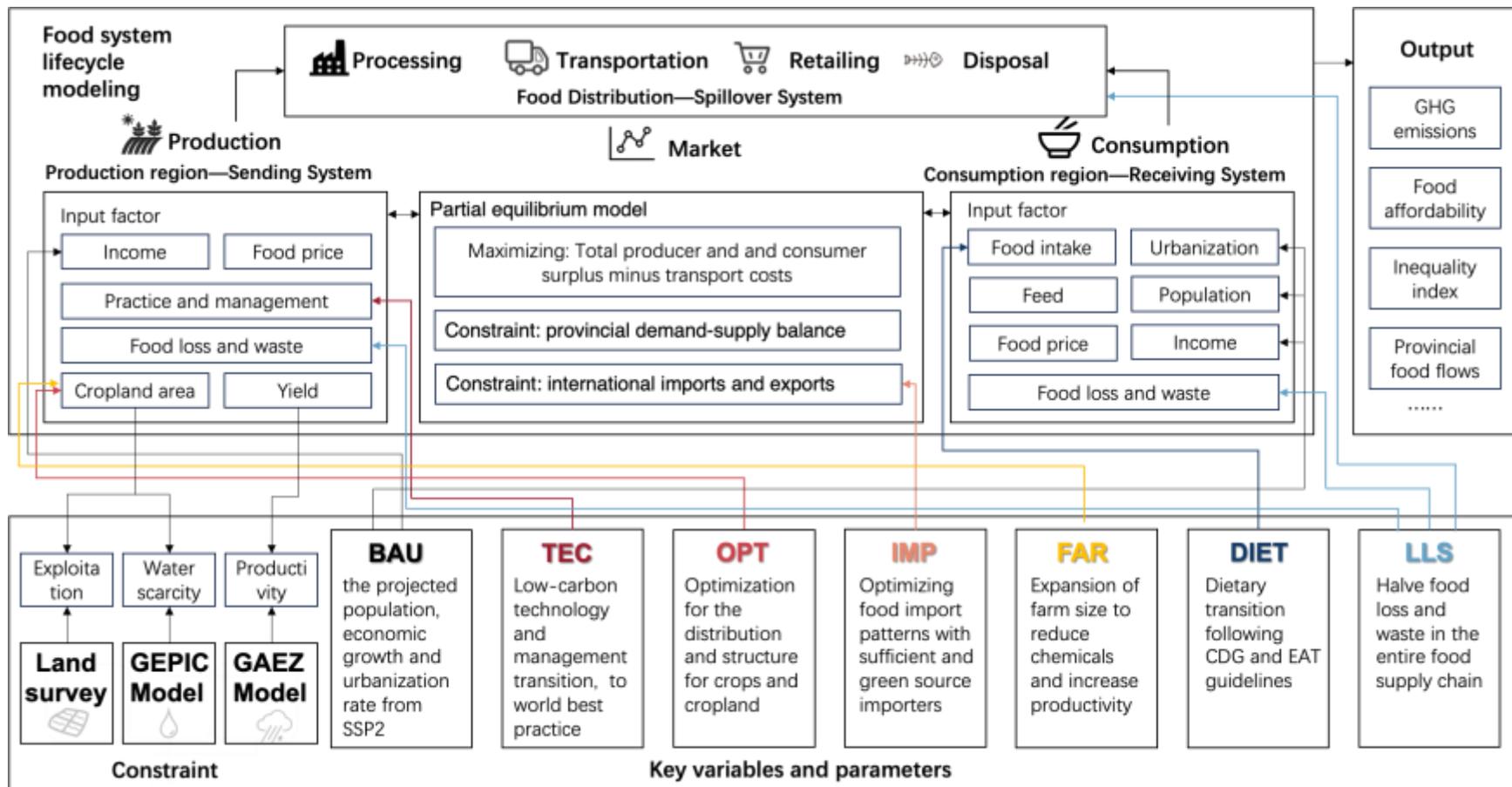
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 932 **Fig. 4. Performance of combined-action scenarios in mitigating China's food system**  
 933 **carbon emissions by 2060. (a) and (b)** Combined-action scenarios (2060) under CDG (a)  
 934 and EAT (b) adoption. The length of each color bar represents the emission reduction  
 935 potential of individual single-action scenario. The stacked colored columns illustrate the  
 936 cumulative emission reduction potential of each combined-action scenario. Circles labeled  
 937 "0%" denote the reference BAU scenario. The light blue shaded areas at the outer edges of  
 938 the bars represent the additional mitigation, or enhancement effects, stemming from each  
 939 combined-action scenario (see Table 1 for description of strategies). (c) Mitigation  
 940 potential trends of combined-action scenarios (2018-2060; in Mt CO<sub>2</sub>e). The numbers  
 941 beside each colored line indicate the emission mitigation potential of combined action  
 942 strategies. The gray solid lines represent all combination scenario trends. Dashed lines  
 943 represent the food and non-food mitigation targets needed to meet the 1.5 °C (orange) and  
 944 2.0°C (red) climate goals, respectively.



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**Fig. 5 Synergies and trade-offs of combined-action strategies for food system carbon emissions, food affordability and inequality.** (a) and (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

957 affordability inequalities compared to the BAU scenario. Light pink backgrounds in the  
958 second and fourth quadrants indicate trade-offs in regional inequality in food affordability  
959 relative to the BAU scenario. Green background in the third quadrant represents strategies  
960 where reducing inequalities in both food affordability and emissions can be synergistic.  
961 The size of bubbles represents the relative changes in emissions by 2060 compared to the  
962 BAU scenario, while the color reflects the performance of each scenario in balancing  
963 synergies and trade-offs between emissions and food affordability (see Table 1 for  
964 description of strategies).



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 966 **Fig 6. Framework of the integrated assessment model for food system in China.** The Food System Lifecycle Integrated Assessment  
 967 model (FSL-IAM) provides a comprehensive framework for achieving a sustainable transformation of the food system, focusing on  
 968 low-carbon solutions, improved health outcomes, and reduced inequalities. By incorporating various strategies and their combinations,  
 969 the model simulates the impacts on food system GHG emissions, food affordability, and resulting inequalities, which are measured  
 970 using the Theil index. Production transformation strategies include technological upgrades in production (TEC), farm size expansion  
 971 (FAR) and optimization of production space (OPT). Consumption transformation strategies involve dietary transitions following

972 guideline (CDG) and (EAT), and halve food loss and waste (LLS) Supply chain transformation strategies include halve food loss and  
973 waste alongside the food supply chain (LLS) and import patten optimization (IMP). The food lifecycle is connected through the food  
974 supply chain, where production is influenced by the availability of arable land reserves, regional water scarcity, and best attainable  
975 yields. Regional food is modeled using partial equilibrium, which is constrained by the balance between regional supply and demand.

**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.

979 **Data and materials availability:**

980 All data needed to evaluate the conclusions in the paper are present in the paper and/or the  
981 Supplementary datasets S1-S3. The GAMS code used for this analysis are available on Zenodo at  
982 <https://doi.org/10.5281/zenodo.14858955>. Additional data related to this paper may be requested  
983 from the authors.