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

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Abstract

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

37 **Main**

38 China's unprecedented economic growth over the past decades has lifted millions of people out of
39 poverty and hunger while reshaping its food system¹. The rapid change of the country's food
40 system poses pressing challenges to public health, the environment, and livelihoods¹⁻³. Overall
41 dietary quality remains suboptimal, responsible for 51% of all cardiometabolic deaths and 21% of
42 total deaths between 2010 and 2012⁴. Environmentally, with increasing concern about the overuse
43 of nitrogen (N) fertilizer, the country's efforts are particularly devoted to enhancing N use
44 efficiency (NUE)². Food systems and the economy are closely interlinked^{1,5}. Malnutrition results
45 in substantial economic losses at the individual and societal levels. Individuals are estimated to
46 suffer productivity losses amounting to over 10% of their lifetime earnings, while the gross
47 domestic product (GDP) lost to malnutrition can range from 2% to 3%⁶. The inefficient food
48 system creates 19% of food losses⁷, suggesting that 4%–5% of China's workforce work in vain^{8,9}.

49 The global development agenda recognizes the imperative of comprehensively transforming the
50 food system for sustainable development¹⁰⁻¹³, and policymakers in China acknowledge this
51 necessity^{1,2}. Achieving a sustainable food system transformation, framed as green agriculture with
52 high-quality development in the Chinese context, requires high standards not only for sustainable
53 agricultural production but also in terms of food consumption and public health^{1,5}. However, the
54 feasibility of achieving future targets for the Chinese food system is yet understood, and trade-offs
55 and co-benefits need to be unveiled¹⁴. The existing studies often neglect socioeconomic and
56 biophysical dynamics on which the food system hinges and focus on selective policy measures,
57 such as nutrient management³ and dietary changes⁴.

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

62 We begin the assessment with a baseline scenario (BASE_{SSP2}) that is constructed from the middle-
63 of-the-road Shared Socioeconomic Pathway SSP2^{17,18} and incorporates the Chinese food system
64 *status quo*. We then consider three package scenarios that correspond to three respective sets of
65 sustainable transformation measures of the food system based on China-specific data and
66 conditions (Extended Data Fig. 1 and Extended Data Table 1). Set A (*Diets* scenario) entails
67 transitioning towards dietary recommendations of the EAT-Lancet Commission¹², while
68 incorporating Eastern healthy dietary patterns proposed by the Chinese Dietary Guidelines
69 (CDG)¹⁹ for China, along with targets to reduce food waste, overcome undernutrition and halve
70 overnutrition by 2050. These ambitious targets align with recent developments in China, including
71 updates of CDG and the release of the Healthy China 2030 Plan²⁰, which emphasize responsible
72 and healthy diets to promote public and planetary health. Set B (*SustEnvironment* scenario)
73 prioritizes sustainable agriculture management and land use, along with strengthened ecological
74 conservation and climate change mitigation. This aligns with China's environmental protection
75 goals for soil²¹, air²², and water²³. China's recent pledge for climate neutrality by 2060 underscores
76 its commitment to reduce greenhouse gas (GHG) emissions¹. Biodiversity conservation and
77 regeneration are also high priorities, exemplified by CBD COP 15²⁴. Set C (*Livelihoods* scenario)
78 prioritizes socioeconomic progress and lifestyle transformation within and beyond the food system,
79 aiming for livelihood improvement. This is a key objective of the food system transformation,
80 acknowledging the challenges faced by the impoverished producers and consumers who are the

81 most economically vulnerable groups in society since their livelihoods heavily depend on
82 agriculture and are often influenced by social and environmental factors^{15,25–29}. We further
83 integrate all measures from sets A–C into a combined scenario, that is, the Chinese food system
84 transformation pathway (FST_{SDP_China}) to reveal the impacts and the interactions of sets A–C.

85 This study builds on an analysis of a global food system transformation pathway¹⁶ that employs
86 the same benchmark methodology and integrated assessment framework (details in Methods). This
87 ensures that the transformation pathway of the Chinese food system aligns with sustainable
88 development objectives on the global scale while taking into account country-driven multi-
89 objective pathways^{30,31}. The core of this integrated modeling framework is MAgPIE-China (a
90 China version of Model of Agricultural Production and its Impact on the Environment)^{2,32–35},
91 linked with several sectoral models to cover health and livelihood aspects^{13,25}. MAgPIE-China is
92 an agro-economic land system model designed to minimize costs while satisfying the demand for
93 agricultural products. Key assumptions of this modeling analysis include that income drives food
94 waste and productivity increase drives reduction in labor requirement. More details about the
95 assumptions can be found in Extended Data Table 1 and Supplementary Information. We analyze
96 model results from 2020 to 2050 and combine a validation phase from 1995 to 2015 for model
97 quality checks. In addition to health and environmental indicators, we incorporate the aspect of
98 livelihoods to broaden our understanding of the impacts related to social progress, which is
99 measured in terms of agricultural expenditure, population in poverty, agricultural employment,
100 agricultural wage, bioeconomy supply, and production costs.

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

116

117 **Results**

118 We first assess the social and environmental impacts of the Chinese food system in the BASE_{SSP2}
119 scenario. Under current trends, we project that China's public health would continually face
120 challenges related to malnutrition. The underweight population will approximately halve to 25
121 million in 2050 relative to 2020, while the prevalence of obesity will increase to 202 million people
122 (Fig. 1). The double burden of malnutrition³⁷ is inextricably linked to suboptimal diets, which are
123 among the top five risk factors that are strongly associated with health and longevity⁵. Animal-
124 sourced and empty-calorie foods account for 52% of daily calorie intake in 2050 (Fig. 3a), leading

125 to poorer dietary quality in terms of the Chinese Healthy Eating Index (CHEI) and EAT-Lancet
126 Diet Index (EATDI) relative to 2020 (details in Methods). The projected premature mortality
127 attributed to suboptimal diets in China will fall by 2 million in 2050 compared to 2020, but still
128 amount to 38 million years of life lost (YLLs) annually, equivalent to an economic loss of 966
129 billion USD_{17ppp} per year and 1.4% of the country's projected GDP in 2050 (details in
130 Supplementary Information).

131 The food system is projected to remain a major driver of environmental damage in the BASE_{SSP2}
132 scenario assuming no additional measures are implemented, rendering the UN Agenda 2030 for
133 SDGs and Paris Climate Agreement unachievable even by 2050 (Fig. 1). The projected
134 biodiversity intactness index (BII) for all land types (details in Methods) slightly increases in 2050
135 by 0.4 points from 73.9 in 2020, even in the absence of specific measures addressing biodiversity
136 issues. However, the biodiversity hotspot areas in Northern China would remain at lower BII levels
137 (Fig. 2a). This is largely due to the afforestation driven by the Nationally Determined
138 Contributions (NDCs) and the reduction in other natural vegetation (Supplementary Fig. 1).
139 Northwest China has even lower crop diversity, measured as Shannon Index (Fig. 2b). Yet, crop
140 diversity is crucial for enhancing agricultural resilience and adaptability in the face of changing
141 environmental conditions. Annual GHG emissions from agriculture, forestry, and other land use
142 (AFOLU) in 2050 would only decrease to 0.7 Gt CO₂eq/yr (Supplementary Fig. 2), indicating that
143 more ambitions are required to meet the climate neutrality target of 1.5 °C. With inefficient
144 fertilizer use and nutrient management, we project a high N surplus of 35 Mt N/yr in 2050,
145 overshooting the country's N planetary boundary of 26 Mt N/yr^{2,38} and thus exacerbating air and
146 water pollution³, particularly in the North China Plain and the Taihu Basin where agricultural
147 production is concentrated (Fig. 2c). The cumulative N-related emissions from 2020 to 2050 would
148 amount to 625 Mt N (Supplementary Fig. 3), of which N₂O emissions constitute 11 Gt CO₂eq. The
149 violation of environmental water flow requirements is projected to further deteriorate to excessive
150 withdrawals of 23 km³/yr (+44%) in 2050, with water scarcity still prevailing in North China (Fig.
151 2d).

152 With increasing labor productivity, agricultural employment is projected to decline by 93 million
153 agricultural workers in 2050 compared to 2020, with 47 million jobs remaining in primary
154 agricultural production (Fig. 1). Daily food waste would further increase to 927 kcal/capita in 2050
155 due to increasing income (Fig. 3b), amounting to a total food waste of 126 million tons. This is
156 equivalent to 18% of agricultural labor bound to unproductive activities, indicating the large
157 inefficiency of the food system¹. The population size within the low-income group (i.e., below
158 3.65 USD_{17PPP}/capita/day) is projected to decrease by 94% between 2020 and 2050 (Fig. 1).
159 Despite this substantial improvement, the remaining poor are particularly vulnerable to external
160 shocks³⁹⁻⁴¹, highlighting the need for inclusive food system transformation.

161 **Co-benefits of China's sustainable food system transformation**

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

166 Regarding public health, the sustainable transformation of the Chinese food system is projected to
167 have large benefits in terms of a 76% decrease in premature mortality in 2050 compared to the
168 BASE_{SSP2} scenario, avoiding a 1% loss of the country's 2050 GDP. Based on our exogenous

169 dietary assumption in accordance with the CDG, the intake of animal-based foods is partly
170 substituted by plant-based foods with a high share of nutritious and healthy vegetables and fruits.
171 The daily intake of animal-based foods (including ruminant meat, pork, poultry, eggs, milk, and
172 fish) would be 290 kcal/capita in 2050, a 62% reduction compared with the BASE_{SSP2} scenario.
173 The slightly lower CHEI in 2050 relative to 2020 is mainly attributed to the reduced intake of eggs
174 (Supplementary Fig. 4). While our dietary scenario and CHEI both align with CDG
175 recommendations, there is a distinction between the two in terms of their approach. In our scenario,
176 we have established an upper limit on egg intake, whereas CHEI promotes egg consumption
177 without imposing any upper bound. The per capita daily intake of sugar and alcohol would also
178 decrease by 28% and 75%, respectively (Fig. 3a). In contrast, the intake of plant-based foods with
179 high nutrient density would substantially increase. The intake of pulses and oilseeds including
180 soybeans and nuts will increase to 261 kcal/capita/day in 2050, and the intake of vegetables and
181 fruits will increase to 484 kcal/capita/day (Supplementary Fig. 5). The finding corroborates
182 existing studies about the potential health benefits of adopting healthy plant-based diets⁵.

183 Environmentally, in the FST_{SDP_China} scenario, natural land with high biodiversity intensity is
184 restored, leading to an overall increase in BII to 75.5 in 2050, while the overall crop area diversity
185 remains unimproved compared to the BASE_{SSP2} scenario (Fig. 1). Spatially, there are substantial
186 improvements in BII in Southwest China where biodiversity hotspots are located (Fig. 2a). Crop
187 area diversity in Central and Northeast China would also improve, which are the major areas of
188 grain production (Fig. 2b). In contrast, it would become worse in South China. Land-use change
189 in 2050 compared to the BASE_{SSP2} scenario is featured with decreasing total areas of cropland and
190 pasture by 68 Mha and increasing forest areas of 30 Mha and natural land areas of 37 Mha
191 (Supplementary Fig. 6). The N surplus can be decreased by 46% (16 Mt N/yr) in 2050 compared
192 to the BASE_{SSP2} scenario (Fig. 2c) and be operated well below the country's N planetary
193 boundary^{3,38}. Cumulative N-related emissions from 2020 to 2050 can be reduced by 51%
194 compared to the BASE_{SSP2} scenario, of which N₂O emissions decrease by 49% (Supplementary
195 Fig. 3). This is largely due to further NUE improvement via fertilization standards for different
196 regions and crops, promoting high-efficiency fertilizers, and adopting new fertilization methods²
197 (Extended Data Fig. 2). The negative annual GHG emissions of 0.6 Gt CO₂eq/yr in 2050 suggest
198 that China can achieve climate neutrality in its AFOLU sector, which is critical for the country's
199 overall climate neutrality target in 2060¹. The eradication of excessive water withdrawals in 2050
200 is feasible in the sustainable transformation pathway (Fig. 2d) where stringent water conservation
201 is introduced jointly with a shift towards healthy diets.

202 For the livelihoods, the food system sustainable transformation in China would lift a large fraction
203 of the population out of the income group below 3.65 USD_{17PPP}/capita/day, by 87% decrease to
204 1.4 million people compared to the BASE_{SSP2} scenario, of which 0.2 million live below the income
205 level of 2.15 USD_{17PPP}/capita/day. This is largely due to the rapid economic growth in China
206 projected by the sustainable development pathway following SSP1. The income inequality is
207 decreased given that there is a decrease in the ratio of mean over median income (Supplementary
208 Fig. 7). The annual expenditure for agricultural commodities is almost halved to 459 USD/capita
209 in 2050 compared to the BASE_{SSP2} scenario, resulting from increased intake of healthy and
210 nutritious foods that are more affordable.

211 Overall employment in agricultural production is projected to shrink by 32% compared to the 2050
212 BASE_{SSP2} scenario (Fig. 1 and Fig. 3c), indicating the enhanced efficiency of the food system and
213 a structural change. The sustainable transformation pathway entails a 64% increase in labor

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

236 **Trade-offs and co-benefits between public health, the environment, and** 237 **livelihoods**

238 China's food system transformation pathway (FST_{SDP_China}) generates substantial co-benefits for
239 public health, the environment, and livelihoods. However, policy measures in China are often
240 initiated and implemented by individual sectors and ministries, leading to less coordinated
241 transformations. To understand the effects of these sector-specific measures, we also examine the
242 package scenarios of *Diets*, *SustEnvironment*, and *Livelihoods*. This approach provides evidence
243 of the co-benefits and trade-offs in the absence of fully coordinated transformation pathways (Fig.
244 4 and Extended Data Fig. 3).

245 The scenario *Diets* exhibits the highest level of co-benefits in terms of outcomes among the three
246 sets of measures (Extended Data Fig. 3b). Moving towards diets better aligned with the CDG
247 synergistically improves nutrition and health outcomes (Fig. 4c) can reduce poverty (Fig. 4c) and
248 agricultural employment (Fig. 4g), and has positive impacts on the environmental outcomes (Fig.
249 4b, d). The transition to diets with higher intake of plant-based foods entails GHG emissions
250 reductions within the AFOLU sector (Fig. 4d). Crop area diversity increases compared to the 2050
251 BASE_{SSP2} scenario (Fig. 4b), in particular for most of China's major grain production areas
252 (Supplementary Fig. 11b). Improving diets leads to a 29% decrease in agricultural employment in
253 2050 relative to the BASE_{SSP2} scenario (Fig. 4g), as the primary contributor to structural
254 transformation and efficiency enhancement of the food system. With regards to the three individual
255 measures in the *Diets* scenario, the reduction in per capita daily total calorie intake in this scenario
256 results in a 0.9% decline in agricultural employment (Supplementary Fig. 10). The reduction in
257 food waste reduces agricultural employment by 10% while shifting Chinese diets in concert with
258 the dietary guideline contributes to a 19% reduction of agricultural employment. Animal-sourced

259 food consumption (i.e., food intake and waste) will reduce by 64% in 2050 compared to the
260 baseline level, leading to a 58% (15 million) reduction in employment in livestock production and
261 77% decline in feed production (from 7.2 million to 1.6 million) (Supplementary Fig. 12). Despite
262 the overall downward trend of agricultural employment, it is worth noting that shifting food
263 consumption in accordance with the dietary guideline increases consumption of plant-based foods
264 including vegetables, fruits, pulses, and nuts, which is expected to employ an additional 4.1 million
265 people.

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

285 The *Livelihoods* scenario prioritizes enhancing livelihoods, characterized by higher agricultural
286 wages, increased labor productivity, rapid economic growth, and low population growth. The
287 assumed increase in agricultural wages plays a crucial role in supporting the income growth of
288 agricultural workers. The population in the low-income group below 3.65 USD_{17PPP} per capita per
289 day in China would decrease to 1.4 million people even though agricultural employment faces a
290 sharp decline (Fig. 4i). It is worth noting that the emphasis on social outcomes can have mixed
291 impacts on public health and environmental sustainability. There are both decreases in the
292 underweight population and premature mortality in 2050 (Fig. 4a), while the number of people
293 with obesity is projected to increase to 227 million in 2050 due to the persistence of suboptimal
294 diets along with the growing income, characterized by a high consumption of red meat (Extended
295 Data Fig. 3d). Concerning the environmental outcomes, GHGs emitted in the AFOLU sector
296 would decrease by 354 Mt CO₂eq mainly due to the external energy transition in the context of
297 overall sustainable development (Fig. 4f). However, biodiversity (Fig. 4h), crop area diversity (Fig.
298 4e), and water scarcity (Fig 1) are expected to further deteriorate relative to the baseline level. The
299 expansion of bioenergy production could lead to more severe water scarcity and a decrease in crop
300 area diversity due to the cultivation of bioenergy crops. To provide materials for the bioplastic and
301 construction industries, there would be a decrease in BII due to the growing timber demand
302 (Extended Data Fig. 2).

303

304 **Discussion**

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

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

327 **Reconciling trade-offs in China's food system transformation**

328 Trade-offs and co-benefits arise in the proposed food system transformation in China. For instance,
329 stringent biodiversity and GHG mitigation efforts in the *SustEnvironment* scenario may
330 unintentionally reduce crop diversification and exacerbate poverty, impacting low-income
331 populations who rely on diverse crops for dietary quality⁴⁴ (Extended Data Fig. 2). In the
332 *Livelihoods* scenario, measures for energy transition and capital substitution may adversely affect
333 crop area diversity and the adherence to regional nitrogen surplus boundaries (Extended Data Fig.
334 2). The *Diets* Scenario emphasizing changing food consumption is found to be the most synergistic
335 among the three package scenarios (Extended Data Fig. 3). Particularly, adhering to the
336 recommended dietary guidelines is a crucial lever for transforming the Chinese food system
337 towards sustainability^{1,12,13,31}. In line with the existing studies on dietary transformation^{13,15},
338 dietary shift has the potential to generate substantial positive impacts on multiple indicators related
339 to the sustainability of the food system, such as reducing GHG emissions, improving public health
340 outcomes, and preserving natural land and water resources.

341 Addressing negative impacts requires a combination of measures that reconcile trade-offs across
342 public health, the environment, and livelihoods. Our model results indicate that the integration of
343 these three package scenarios shows large improvements across all indicators, confirming the
344 effectiveness of coordinated policy approaches. The agricultural sector faces a decline, with
345 employment projected to decrease to 2.4% of the total population by 2050, similar to trends in the
346 United States (0.8%) and Japan (1.7%) in 2020⁴⁵. An aging agricultural workforce with 51% of its
347 workforce over the age of 55 by 2050, yet younger than Japan's current average age of 66.8 years⁴⁶.

348 The exit of smallholder farmers can facilitate land consolidation and agricultural mechanization,
349 supporting our expectations of continued growth in agricultural wages and labor productivity.
350 However, additional policy measures are necessary to support both the sector and farmers.
351 Agriculture support in terms of subsidies in China increased from 9.5% of production value in
352 2000–2002 to 17.6% in 2019–2021⁴⁶, but distortions due to subsidies suggest a need for
353 reallocation towards infrastructure investment, research on nutritious and sustainable food
354 alternatives⁴⁷, and safety nets for vulnerable groups in rural areas^{34,48}. The EU Common
355 Agricultural Policy serves as a model for smoothing transitions, emphasizing direct payments,
356 investments in research and development, training for unskilled labor, and rural development⁴⁶.

357 Potential new employment opportunities are emerging in other sectors such as bioenergy
358 production. Bioenergy with Carbon Capture and Storage (BECCS) could offset part of the negative
359 impacts of the food system transition on employment and also contribute to GHG emissions
360 reduction⁴⁹. Moreover, broadening the scope has the potential to transform the nutrition and health
361 industry into a powerful driver of both health improvement and livelihoods. This holistic approach
362 considers not only the health outcomes but also the environmental and livelihood issues, creating
363 new employment opportunities across various sectors, including caregiving, nursing, medical
364 services, and food and nutrition education¹.

365 **A guiding pathway to support evidence-based policymaking**

366 This study provides a detailed analysis of potential measures for transforming the Chinese food
367 system and identifies domains where urgent changes are needed. By doing so, we offer model-
368 based insights on where significant efforts should be devoted, where coordinated governance is
369 required, and which combined measures are needed. A sustainable food system can only be
370 reached through coordinated governance because of the wide range of social and environmental
371 problems connected to the food system. The food system needs diverse and varied policy
372 instruments due to its greater complexity compared to the energy system, and a single measure
373 like GHG pricing alone is insufficient¹. Our findings support the establishment of a monitoring
374 framework to inform future actions and policies for the Chinese food system transformation
375 towards achieving the UN Agenda 2030^{16,42}.

376 Changing dietary behaviors is essential yet challenging, requiring large shifts in individual and
377 societal practices^{1,50}. Educational programs, information provision^{51,52}, and behavioral nudges can
378 raise awareness of food choices⁵³, while regulations or taxation can provide economic incentives
379 to promote sustainable food choices⁵⁴. In the distinct context of Chinese food culture, refining the
380 national dietary guidelines to incorporate the Eastern healthy dietary pattern¹⁹, the planetary health
381 diet¹², and elements of Chinese cuisine specialty can help navigate the food system transformation.
382 Technological innovations in cold-chain logistics, high-barrier packaging, and blockchain can
383 further reduce food loss and waste, enhancing food safety and quality⁵⁵. Financial support, income
384 transfers, and investments in infrastructure and technological innovation are crucial for the
385 adoption of green technologies and the enhancement of human capital. These efforts not only
386 contribute to productivity growth and sustainable agriculture but can alleviate poverty^{15,25}.

387 Policy measures are under the responsibility of various governmental branches and their success
388 can hinge on coordination with other measures. While understanding individual measures is crucial
389 for implementing transformation pathways, coordinating policies to balance sustainability aspects
390 is equally important. A coordinated governance system is necessary to align policies for co-
391 benefits and minimize trade-offs, which is particularly challenging in China's sector-specific

392 policy environment. A rigorous, science-based monitoring framework can facilitate evidence-
393 based policymaking and hold key actors accountable during the transformation process^{1,42}.
394 Moreover, the country's localized initiatives can have a substantial impact on the global food
395 system through the international market. By adopting eco-labeling and certification schemes,
396 China can foster environmentally friendly practices among its trade partners⁵⁶. As a major importer
397 of agricultural products, the monitoring framework of China's food system transformation can
398 better facilitate global food system transformation.

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

411 **Methods**

412 **MAGPIE-China**

413 The cornerstone of this analysis relies on the MAGPIE (Model of Agricultural Production and its
414 impact on the Environment) partial equilibrium model³², which is an agro-economic land system
415 model designed to minimize costs while satisfying the demand for agricultural products. The
416 model is developed to describe the land and food sectors and assess the associated consequences
417 for sustainable development under different future scenarios. A more detailed description of the
418 MAGPIE model can be found in the Supplementary Information. To facilitate the study of China's
419 food system transformation pathways, we further develop a China-specific version of the MAGPIE
420 land system modeling framework (MAGPIE-China) to incorporate China-specific data and
421 conditions. Taking into account China's fertilizer policy reform, we estimate the changes in N
422 fertilizer price and the efficiency of agricultural nutrient management induced by the reform and
423 introduce them into the MAGPIE model². For specific water protection measures in China, we set
424 an upper limit on agricultural freshwater use. Further, we calibrate China's agricultural irrigation
425 efficiency using Chinese official data (0.536 in 2015, 0.565 in 2020) and targets (0.58 for 2025,
426 0.6 for 2035)³⁵. We also consider the policy of maintaining minimum cropland³⁴ in the model with
427 a threshold of 120 million hectares. These China-specific measures are applied across all scenarios
428 in this study. The model runs in a dynamic recursive manner from 2020 to 2050 with a five-year
429 interval. This study uses a mapping of 16 world regions and 200 simulation units (Supplementary
430 Fig. 13) according to their geo-economic conditions. The regional environmental outcomes are
431 further disaggregated to 0.5-degree resolution.

432 In accordance with the food system modeling framework applied in the analysis of a global food
433 system transformation pathway¹⁶, MAGPIE-China is linked to several models to cover health,
434 environmental, and livelihoods outcomes. The food intake and food waste are estimated based on
435 a food demand model, driven by demographic composition of the population, physical activity
436 level, body height distribution, and income⁴⁷. Dietary composition shifts are projected for four
437 major food categories: animal-sourced foods (including ruminant meat, pork, poultry, eggs, milk,
438 and fish); empty-calorie foods (including oils, sugar, and alcoholic beverages); vegetables, fruits,
439 and nuts; and staple foods. The four groups are then further divided into 25 food items based on
440 the relative share of individual food products within major food groups. The biophysical
441 information including crop yields, water requirements, carbon stocks, and water availability are
442 input from a vegetation, crop, and hydrology model LPJmL (Lund-Potsdam-Jena model with
443 managed Land)⁵⁷. The terrestrial biodiversity is assessed using BII^{58,59}, which measures net
444 changes of organism abundance based on the loss of forest, non-forest vegetation, and age-class
445 vegetation. A poverty model²⁵ is run as a post-processing of the MAGPIE-China model results.
446 The macro-economy and energy model REMIND⁶⁰ provides bioenergy demands and GHGs prices.
447 Furthermore, the food demand model is linked with a health model to estimate the health impacts
448 of dietary transition⁶¹.

449 **Health model**

450 We employ a comparative risk assessment (CRA) method⁶¹, which links changes in risk factors
451 such as high consumption of red meat, reduced consumption of fruits and vegetables, being
452 underweight, and overweight to changes in cause-specific mortality. The endpoint diseases
453 considered in this study include coronary heart disease (CHD), stroke, type-2 diabetes mellitus

454 (T2DM), cancer (in aggregate and as colon and rectum cancers), and respiratory disease. The
455 baseline body weight distribution and the corresponding energy intake are projected based on a
456 regression model using country, sex, and age-specific anthropometric data⁴⁷. The relative risk
457 estimates are adopted from a meta-analysis of prospective cohort studies^{62–66}. The age-specific
458 mortality and population data are adopted from the Global Burden of Disease project⁶².

459 Two dietary indices, the Chinese Healthy Eating Index (CHEI) and the EAT-Lancet Diet Index
460 (EATDI) are calculated to understand the overall dietary quality across scenarios. The CHEI is
461 developed based on the CDG and Chinese dietary habits^{67,68}. In China, the intake of 12 food groups
462 (total grains, whole grain, mixed beans, tubers, total vegetables, dark vegetables, fruits, dairy,
463 soybean, fish and seafood, poultry, eggs, seeds, and nuts) should be increased, while the intake of
464 five food groups (red meat, cooking oils, sodium, added sugar, and alcohol) should be decreased
465 to reach a moderate level. Higher scores on the CHEI indicate better adherence to the CDG. As
466 the MAgPIE-China model does not consider whole grain, mixed beans, and sodium, these groups
467 are excluded from our calculation. A detailed scoring standard of the CHEI can be found in Yuan
468 *et al.*⁶⁷. The EATDI is a metric for gauging how closely people adhere to the EAT-Lancet diet⁶⁹.
469 The index consists of 14 food groups, including seven emphasized food groups (vegetables, fruits,
470 unsaturated oils and palm oil, legumes, nuts, whole grains, and fish) and seven limited groups (beef
471 and lamb, pork, poultry, eggs, dairy, potatoes, and added sugar). Each food group is given a score
472 of 0-3, and a higher score indicates higher adherence to the intake target. Since the index is based
473 on an energy intake of 2500 kcal/capita/day, we rescale the intake of each group according to total
474 calories across scenarios when calculating the EATDI.

475 **Poverty model**

476 To project the income distribution, we apply an inequality and poverty post-processing model built
477 originally for global REMIND-MAgPIE scenarios²⁵ to the MAgPIE-China scenarios. Starting
478 from scenarios of the Gini coefficient for the Shared Socioeconomic Pathways (SSPs)⁷⁰, we
479 account for food expenditure changes due to food system measure implementations by calculating
480 their impacts on real incomes and inequality levels. Future poverty headcounts under different
481 poverty lines are estimated using the new average income and Gini coefficients, with a regression
482 model fit to recent World Bank poverty and inequality data of around 130 countries. We notice
483 that this globally calibrated model may underestimate the pace of poverty reduction in China in
484 recent years (i.e., reporting higher poverty headcounts than the latest historical data). An exact
485 comparison is complicated by the effects of the COVID-19 pandemic. We also implement a
486 redistribution of tax revenue to the population in scenarios with CO₂ taxes, where the increased
487 production costs lead to higher expenditure on agricultural products and lower real income. Further,
488 a redistribution without changing the level of inequality to the entire population is assumed in the
489 *MinWage* scenario as we cannot specify the agricultural income and income from other sources in
490 our data¹⁶.

491 **Scenario design**

492 We explore the sustainable development pathways of the Chinese food system by adopting a
493 systematic approach aligned with a global sustainable food system transformation while explicitly
494 considering impacts with regard to public health, the environment, and livelihoods^{15,16}.
495 Additionally, we consider three sets of food system measures representing distinct transformation
496 pathways that prioritize public health, the environment, and livelihoods, respectively, to
497 understand the co-benefits and trade-offs among proposed indicators. Based on the policy

498 background of China, we implement specific measures on diet, nitrogen, water, and cropland
499 management for China, while the rest of the world still follows general settings in each scenario
500 that is in accordance with the global study^{15,16}.

501 **BASE_{SSP2}**

502 The BASE_{SSP2} scenario is the baseline for our study. We use the Shared Socioeconomic Pathway
503 (SSP) projections for regional development of GDP, population, physical activity level, etc. The
504 BASE_{SSP2} scenario follows the *middle-of-the road* (SSP2) path which projects no significant shift
505 from historical patterns. Meanwhile, climate change impacts are taken into account in the
506 projections of yields, water demand and availability, carbon, and land dynamics. To reflect
507 regional efforts on combating climate change, the NDCs are adopted for future afforestation. Food
508 demand and waste are modelled endogenously, driven by socioeconomic factors and demographic
509 trends derived from historical data, calibrated to align with regional food demand reported in
510 FAOSTAT⁷¹. All mapped regions follow these settings in this baseline scenario.

511 **Food System Transformation in the Context of a Sustainable Development Pathway in China** 512 **(FST_{SDP_China})**

513 The FST_{SDP_China} scenario incorporates targeted efforts in China to promote healthy diets, improve
514 nitrogen management, and enhance water management, alongside global actions for a
515 comprehensive transformation of the sustainable food system (FST_{SDP})¹⁶. For diets and food
516 demand, divergent from the baseline level determined endogenously in BASE_{SSP2}, this scenario
517 follows a convergent transition from 2020 to 2050, aligning with the dietary intake targets
518 exogenously set in accordance with the CDG¹⁹. With respect to nitrogen, we first employ a
519 difference-in-differences (DID) econometric method and country-representative household-level
520 survey data in China to estimate the effects of the policy of “Zero Growth in Synthetic Fertilizer
521 Use” on fertilizer use and yields. We then incorporate the changes in nitrogen inputs and outputs
522 into the nitrogen budget to estimate the changes in soil nitrogen uptake efficiency (SNU_{pE}), which
523 is used as a parameter for the improvement of agricultural nutrient management efficiency in the
524 model. Detailed information about the parametrization of SNU_{pE} is documented in Wang *et al.*².

525 For the whole world, a comprehensive food system transformation scheme is adopted from
526 Bodirsky *et al.*¹⁶. The food system transformation aims at global sustainable development and
527 simultaneously implements policy measures concerning healthy diet, environment protection, and
528 livelihood improvement. While China gradually follows the CDG, we assume the dietary structure
529 of countries and regions except China’s transition towards diets proposed by the EAT-Lancet
530 Commission¹². Compared with the baseline scenario, a food waste target is proposed which begins
531 in 2020 and achieves in 2050 with a linear convergence speed. Further, a no underweight and half
532 overweight target is included for all regions.

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

539 Regarding land management, 30% of the global land area will be under protection by 2030, and
540 global afforestation is limited to a maximum of 500 Mha in only tropical area⁷². Simultaneously,

541 the NDC targets (138 Mha of afforestation areas for China by 2030) remain valid at the regional
542 level. Longer crop rotations are incentivized with payments. The non-agricultural water demand
543 follows the SSP1 projection. Regarding GHG pricing, carbon pricing is included with a budget of
544 900 Gt CO₂eq to disincentivize CO₂ emissions from land-use change, and to incentivize
545 re/afforestation or peatland rewetting. Technical mitigation measures for methane mitigation of
546 respective emission sources are introduced via feedback on abatement costs. For biodiversity, zero
547 reduction of aggregated BII in all biomes of each biogeographic realm in each world region is
548 implemented after 2020.

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

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

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564 **Code availability**

565 The MAgPIE code, including the food demand model, is available under the GNU Affero General
566 Public License, version 3 (AGPLv3) via GitHub (<https://github.com/magpiemodel/magpie>). The
567 release (version 4.6.5) used in this paper can be found via Zenodo
568 (<https://doi.org/10.5281/zenodo.7782037>). The technical model documentation is available at
569 <https://rse.pik-potsdam.de/doc/magpie/4.6.5/>). Additional codes and details for all the
570 participating models tailored to China can be provided upon reasonable request. Data analysis was
571 conducted using R (version 4.1.3), GAMS (version 38.3.0), and the libraries of Potsdam Integrated
572 Assessment Modelling (PIAM) (<https://github.com/pik-piam>).

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585 **Contributions**

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

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598 **Competing interests**

599 The authors declare no competing interests.

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

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

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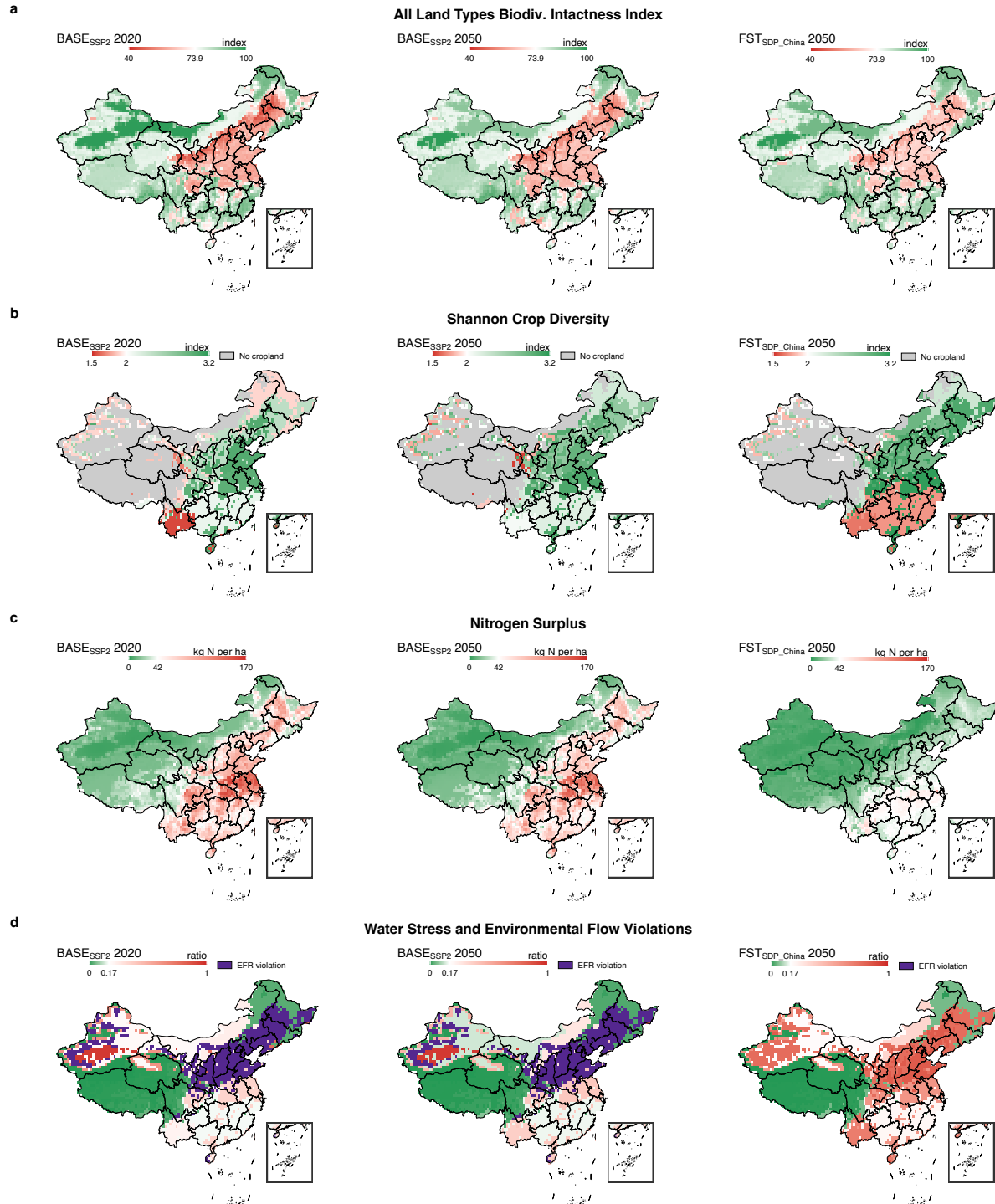
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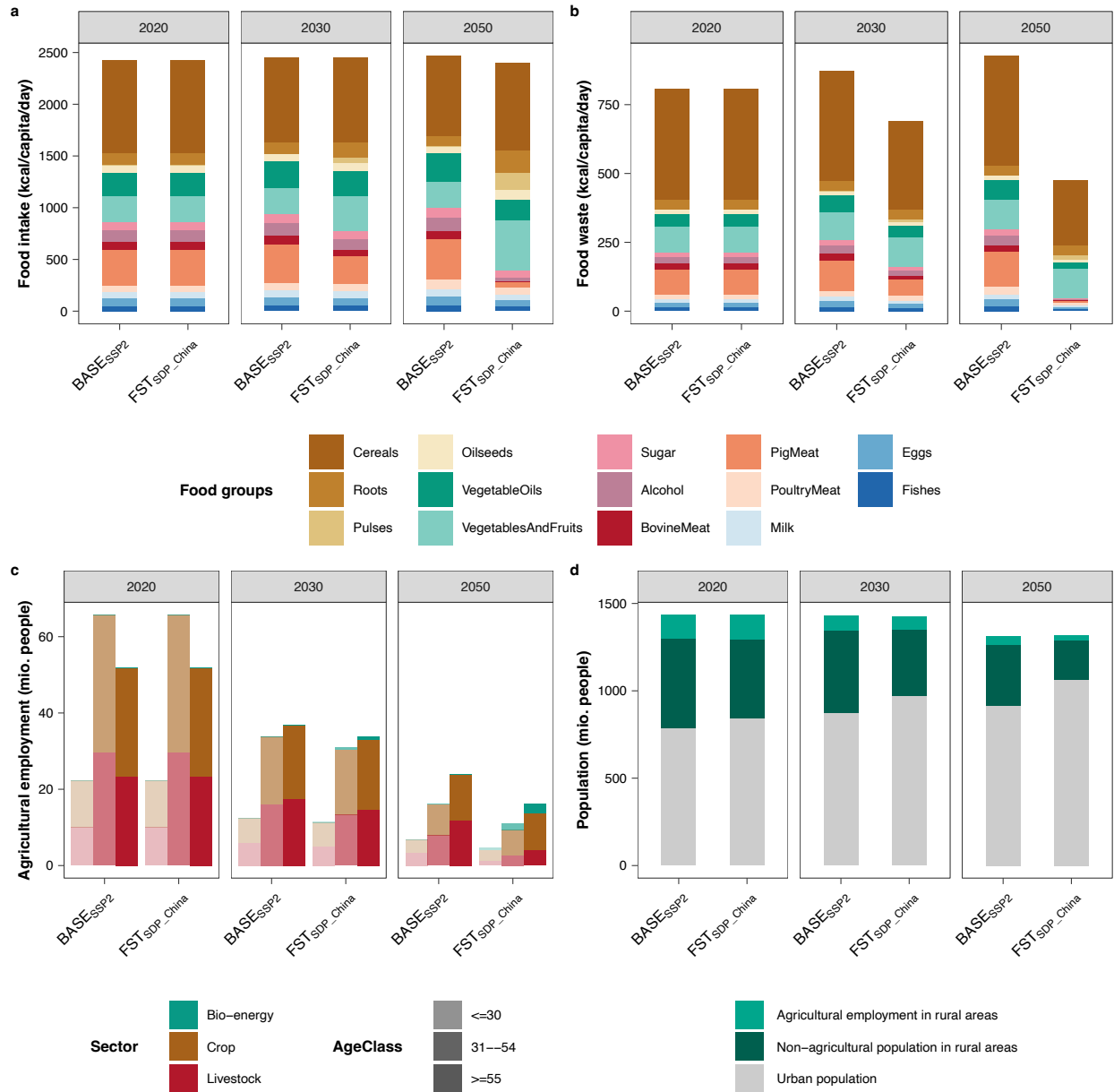
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Fig. 1. Health, environmental, and livelihood indicators associated with the Chinese food system under the BASE_{SSP2}, FST_{SDP_China}, and three package scenarios. The color schemes indicate positive (green) and negative (red) impacts on indicators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



609

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



617

618 **Fig. 3. Dietary patterns and agricultural employment in the BASE_{SSP2} and FST_{SDP_China} scenarios in 2020, 2030,**

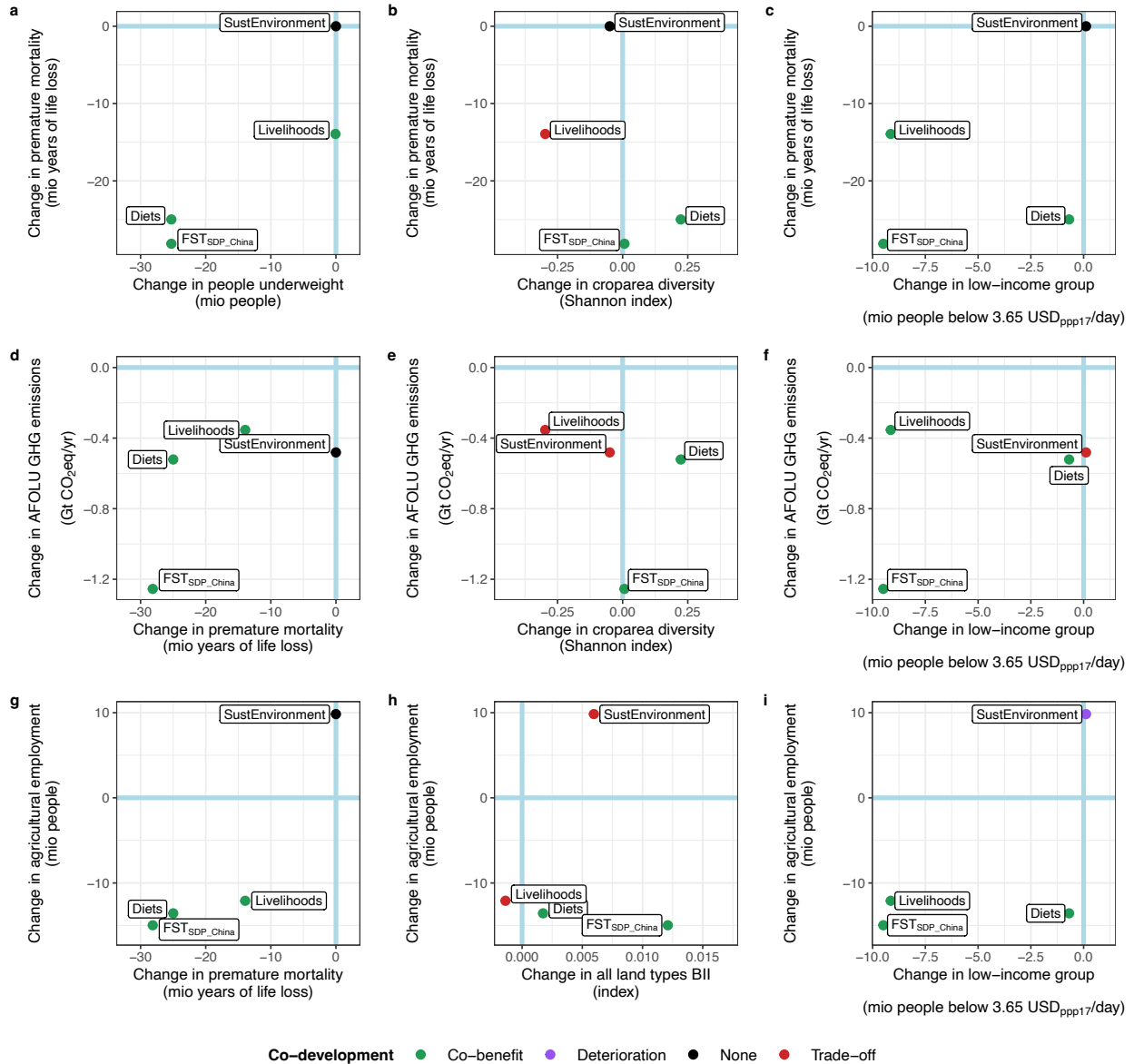
619 **and 2050. (a) Intake of specific food groups. (b) Amounts of food waste by food groups. (c) Agricultural employment**

620 **in bio-energy, crop, and livestock production across the age classes. (d) Distribution between urban and rural**

621 **population and distribution between agricultural employment and non-agricultural population in rural areas.**

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

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