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RESEARCH ARTICLE

STRATEGIES FOR A LOW-CARBON FOOD SYSTEM IN CHINA

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KEYWORDS

greenhouse gas emissions, food system, life cycle assessment, environmental input-output analysis, mitigation strategies

HIGHLIGHTS

- A provincial stage-specific greenhouse gas (GHG) accounting model for the Chinese food system was developed.
- From 1992 to 2017, the net GHG emission from the Chinese food system increased by 38% from 785 to 1080 Tg CO_2-eq.
- In 2017, top GHG emission regions were located in the central and southern China, the North China Plain and Northeast China, while GHG sink regions were Tibet, Qinghai and Xinjiang.
- Total GHG emission from the Chinese food system could be reduced to 355 Tg CO_2-eq in a low-carbon scenario, with enhancing mitigation technologies, transforming diet and its related conditions and increasing agricultural activities contributing 60%, 25% and 15% of the GHG reductions, respectively.

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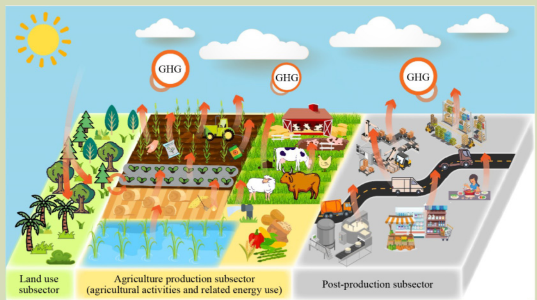
GRAPHICAL ABSTRACT



ABSTRACT

In China, there has been insufficient study of whole food system greenhouse gas (GHG) accounting, which limits the development of mitigation strategies and may preclude the achievement of carbon peak and carbon neutrality goals. The paper presents the development of a carbon extension of NUFER (NUtrient flows in Food chain, Environment and Resources use model), a food system GHG emission accounting model that covers land use and land-use change, agricultural production, and post-production subsectors. The spatiotemporal characteristics of GHG emissions were investigated for the Chinese food system (CFS) from 1992 to 2017, with a focus on GHG emissions from the entire system. The potential to achieve a low-carbon food system in China was explored. The net GHG emissions from the CFS increased from 785 Tg CO_2 equivalent (CO_2-eq) in 1992 to 1080 Tg CO_2-eq in 2017. Agricultural activities accounted for more than half of the total emissions during the study period, while agricultural energy was the largest contributor to the GHG increase. In 2017, highest emitting regions were located in central and southern China (Guangdong and Hunan), the North China Plain (Shandong, Henan and Jiangsu) and Northeast China (Heilongjiang and Inner Mongolia) and contributed to over half of the total GHG emissions. Meanwhile, Xinjiang, Qinghai and Tibet are shown as carbon sink areas. It was found that food-system GHG emissions could be reduced to 355 Tg CO_2-eq, where enhancing endpoint mitigation technologies, transforming social-economic and diet conditions, and increasing agricultural productivities can contribute to 60%, 25% and 15%, respectively. Synergistic mitigation effects were found to exist in agricultural activities.

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1 INTRODUCTION

Reducing greenhouse gas (GHG) emissions and achieving net-zero pledges are becoming more urgent[1]. The latest IPCC report indicated that the average surface temperature has been 1.09 °C higher than the preindustrial period and that extreme meteorological events would be more frequent and severe in the future[2]. China, a country emitting 27% of global GHG emissions[3,4], recently declared its ambitious carbon reduction plan, striving to peak CO_2 emissions by 2030 and achieve carbon neutrality by 2060[5]. This means that China will have to work harder than Western countries to reduce its high emission period. The task and cost of transformation would be enormous[6].

Food system, involving land use, agriculture production and post-production activities, could contribute substantively toward net-zero pledges[7]. In 2015, the global food system has caused 18 Gt CO_2 equivalent (CO_2-eq). GHG emissions, accounting for one third of the total anthropogenic emissions[8]. If the GHG emissions from the global food system continue growing, it alone will result in temperature increases that surpass the 1.5 °C target by 2050[8,9]. Meanwhile, there are 8 to 10.6 Gt CO_2-eq. GHG cost-benefit mitigation potential by land-based measures, especially about one quarter and one third of which are lie in reducing deforestation and enhancing agricultural carbon sequestration, respectively[10]. Therefore, either the whole food system becomes a steppingstone or stumbling block on the road to net-zero emissions depends on how we understand and manage it.

There are still insufficient comprehensive GHG emission accounting studies on the whole Chinese food system (CFS). Most studies have reported the emission induced by agricultural activities[11], followed by LULUC (land use and land-use change) emissions and sequestrations, and finally post-production emissions[12]. Recently, some studies also tried to link agricultural production to post-production or land-use sector. However, the former efforts were always in national scale[13], and the latter efforts did not adequately distinguish the part belonged to food systems[14]. Also, these did not integrate to a consistent framework involving from land use to food consumption, which may hinder policy development in the context of pursuing the goals of reaching peak carbon and carbon neutrality.

In line with the importance and complexity of reducing food system GHG emissions, this study aimed to depict the spatial distribution of GHG emissions from the CFS and explore the emission reduction potential of low-carbon strategies. In our method, we creatively built a stage-explicit food system GHG emission accounting model and conducted a consistent scenario analysis by coupling the accounting model with the FABLE-China calculator[15]. The study presented here provides policymakers with additional insights into achieving net-zero emission food system in China.

2 MATERIALS AND METHODS

2.1 System boundary

We defined 21 GHG emission sources and removals related to food production and consumption, which were further sorted into the LULUC, agricultural production and post-production subsectors (Fig. 1). The net GHG emissions from LULUC contain the emissions induced by land use (LU) of cropland and grassland and from the land-use change (LUC) between cropland, forest and grassland. It needs to be noted that untouched forest is not regarded as a carbon sink in LU because it is not related to food production. Also, due to data availability, only carbon changes in biomass and soil pools are accounted in LULUC subsector. The agricultural production subsector includes not only the emissions of agricultural activities but also the emissions of energy consumption in agriculture production itself (direct energy use) and in production of agricultural inputs (indirect energy use). The post-production subsystem includes the GHG emitted by energy combustion in the food processing, packaging, transport and storage, wholesale and retail, and consumption stages. All GHG emissions are accounted at the provincial scale from 1992 to 2017, except the emissions from the post-production subsystem in Tibet (due to the limited availability of data for Tibet). In addition, the term GHG only refers to CO_2, CH_4, and N_2O in this study, and the values of their global warming potential (GWP) originate from the GWP-100 in the IPCC AR5[16].

2.2 Data sources and processing

We developed an extension of NUFER[17] (NUtrient flows in Food chain, Environment and Resources use model) for carbon to achieve the GHG emission accounting for the whole food system. Specifically, we used a process-based life cycle analysis to calculate GHG emissions in land-use and agricultural subsystems from a bottom-up perspective and used an environmental input-output life cycle analysis (EIO-LCA) to account for the GHG emissions in post-production subsystem from a top-down perspective (Fig. S1).

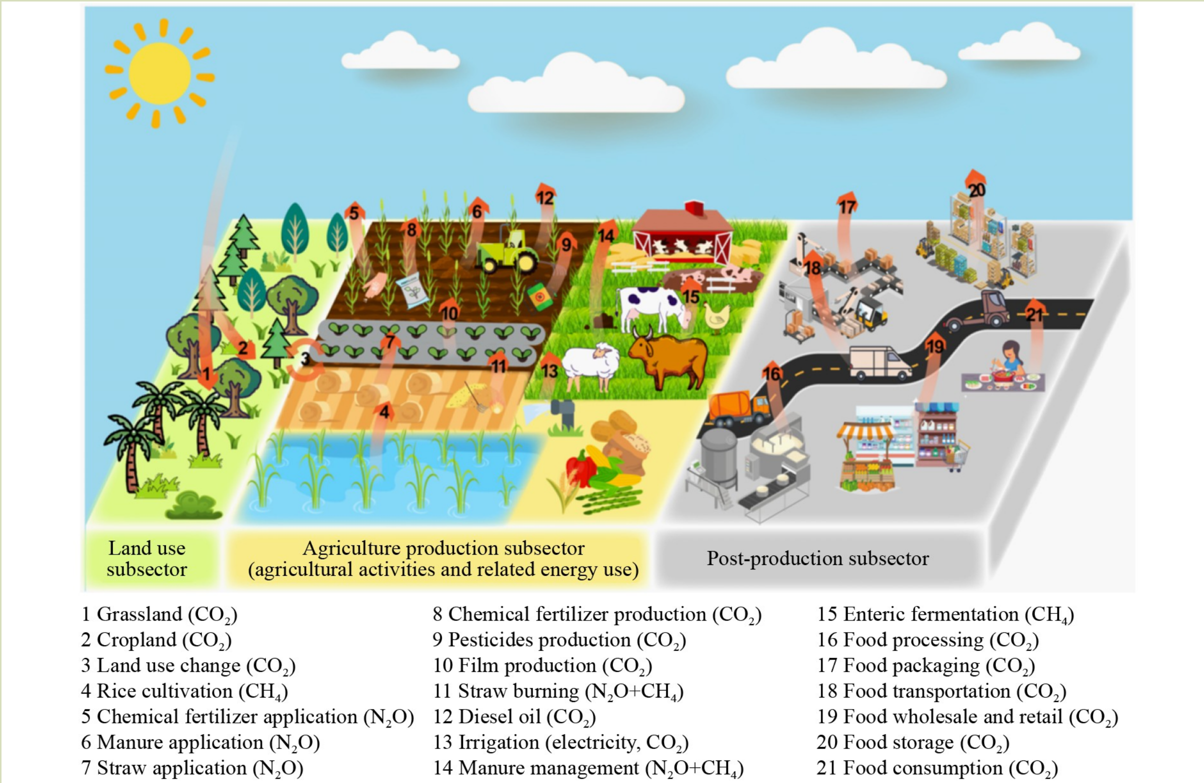

Fig. 1 Scope of the GHG emission accounting for the food system. These icons in the figure were from Vecteezy, and were used within the scope of its license agreement.

Data were further collected based on the requirements of the IPCC guidelines and EIO-LCA (Fig. S1). For GHG emission accounting in land-use subsector, we collected land-use maps (1990–2020), vegetation map and carbon density data from RESDC[18], NTPDC[19] and the most recent literature[20–22], respectively. For GHG emissions from agricultural production, we collected activity data (e.g., crop production, sown area, livestock number, irrigated area, fertilizer use, pesticides use and film use) from statistic yearbooks and the official website of the China National Bureau of Statistics, as well as parameters (e.g., emission factors, nitrogen and carbon contents, root shoot ratios, and straw and manure return rates) from the IPCC Guideline and its derived accounting studies in China[23–26]. For GHG emission accounting in post-production subsystem, multiregional input-output (MRIO) tables and sectoral emission inventories are mandatory, both of which were sources from Shan et al.[27].

Data processing, mainly constructing LUC matrices and adjusting sectors in MRIO tables, supports GHG emission accounting in land-use and post-production subsystems (Fig. S1). For land-use subsector, we loaded LUCC imagines and used the “raster calculator” tool in ArcGIS 10.8 to identify each type of land-use change in 5-year periods from 1990 to 2020 (Table S1). Then we used the ArcGIS tool “zonal statistics as table” to count the LULUC in provincial scale. In post-production subsector, we adapted economic sectors in MRIO tables and emission inventories to each other according to the definitions in industrial classification for national economic activities and calculated GHG emission intensities for each economic sector[28] (Table S2).

2.3 Calculating the GHG emissions from the CFS

2.3.1 Calculations for the GHG emissions and removals in the land-use subsector

We distinguished unconverted land and converted land into 5-year periods from 1990 to 2020, since there are large differences in natural processes and the availability of data between unconverted land and converted land. For unconverted land, the formulae were:

$$E_{\mathrm{lu}} = E_{\mathrm{lu,biomass}} + E_{\mathrm{lu,soil}} \tag{1}$$

$$E_{\mathrm{lu,biomass}}=\sum\nolimits_{i=1}^{2}\mathrm{BioSink}_i\times S_i\times\frac{44}{12}\times\frac{1}{1000}\times\mathrm{GWP}_{\mathrm{CO_2}} \quad (2)$$

$$E_{\mathrm{lu,soil}}=\sum\nolimits_{i=1}^{2}\frac{\mathrm{SD}_{i,t}-\mathrm{SD}_{i,t-1}}{\Delta t}\times S_i\times\frac{44}{12}\times\frac{1}{1000}\times\mathrm{GWP}_{\mathrm{CO_2}} \quad (3)$$

where, E_{lu} denotes the net emission from unconverted land (in Tg CO_2-eq), which consists of net emissions from the biomass carbon pool $E_{\mathrm{lu,biomass}}$ (in Tg CO_2-eq) and soil carbon pool $E_{\mathrm{lu,soil}}$ (in Tg CO_2-eq), respectively; subscript i is land-use type, including cropland and grassland; BioSink denotes the capacity of vegetation to remove carbon[29] (in $\mathrm{kg \cdot m^{-2}}$ C); S denotes the area of a specific land-use type[21] (in $\mathrm{km^2}$); SD denotes soil density[21,22] (in $\mathrm{kg \cdot m^{-2}}$ C); subscript t and t−1 denote the former and latter years of two adjacent study time points, and Δt denotes the interval between these two time points; 44/12 represents the transfer between carbon and carbon dioxide; and $\mathrm{GWP}_{\mathrm{CO_2}}$ is the global warming potential of CO_2.

The changes of carbon pool caused by land-use change are more substantial, but the related directly measured data are limited for China. Therefore, the GHG for converted land used more impact factors compared to that of unconverted land was calculated as:

$$E_{\mathrm{luc}}=E_{\mathrm{luc,biomass}}+E_{\mathrm{luc,soil}} \quad (4)$$

$$E_{\mathrm{luc,biomass}}=\sum\nolimits_{j=1}^{6}\frac{\mathrm{BD}_h-\mathrm{BD}_g}{5}\times\mathrm{Area}_j\times\frac{44}{12}\times\frac{1}{1000}\times\mathrm{GWP}_{\mathrm{CO_2}} \quad (5)$$

$$E_{\mathrm{luc,soil}}=\sum\nolimits_{j=1}^{6}\frac{\mathrm{SD}_{h,\mathrm{ref}}\times\mathrm{IF}_h-\mathrm{SD}_{g,\mathrm{ref}}\times\mathrm{IF}_g}{5}\times\mathrm{Area}_j\times\frac{44}{12}\times\frac{1}{1000}\times\mathrm{GWP}_{\mathrm{CO_2}} \quad (6)$$

where, E_{luc} denotes the net emission from land-use change (in Tg CO_2-eq), including net emissions from the biomass carbon pool $E_{\mathrm{luc,biomass}}$ (in Tg CO_2-eq) and soil carbon pool $E_{\mathrm{luc,soil}}$ (in Tg CO_2-eq); subscript j presents the type of land-use change, which contains all six types of change among forest, cropland, and grassland (in $\mathrm{km^2}$, Table S1); BD is biomass density[20] (in $\mathrm{kg \cdot m^{-2}}$ C); and subscripts g and h are the land-use types at the beginning and end of a 5-year period. Subscript ref denotes the reference status, for example, $\mathrm{SD}_{h,\mathrm{ref}}$ is the reference soil carbon density of land-use type h at the end time point of a specific 5-year period (in $\mathrm{kg \cdot m^{-2}}$ C); and IF means impact factor, which represents the combined impact of climate, agricultural management, and residue inputs on soil carbon[30]. Other symbols were described above.

2.3.2 Calculations for the GHG emissions in the agricultural production subsector

GHG emission accounting for agricultural activities could be simplified by multiplying emission factors by activity data, according to the IPCC guidelines. The formula was:

$$E_{\mathrm{a}}=\sum\nolimits_{m=1}^{6}\sum\nolimits_{n=1}^{2}\mathrm{ef}_{mn}\times\mathrm{AD}_m\times\mathrm{GWP}_n \quad (7)$$

where, E_{a} denotes the emission from agricultural activities (in Tg CO_2-eq, Table 1); subscript m represents the source of emission, for items consistent with the items in second column in Table 1; subscript n is the type of GHG, referring to methane and nitrous oxide; ef and AD represent the emission factor and activity data, respectively (see Table 1 for exact items and references); and GWP_n is the global warming potential corresponding to the GHG type n.

Previous studies have summarized the emission factors for agricultural energy use, which simplified the accounting complexity[12,38]. Their formulae have a similar structure to that of agricultural activities:

$$E_{\mathrm{de}}=\sum\nolimits_{p=1}^{2}\mathrm{ef}_p\times\mathrm{AD}_p\times\mathrm{GWP}_{\mathrm{CO_2}} \quad (8)$$

$$E_{\mathrm{ie}}=\sum\nolimits_{q=1}^{3}\mathrm{ef}_q\times\mathrm{AD}_q\times\mathrm{GWP}_{\mathrm{CO_2}} \quad (9)$$

where, E_{de} and E_{ie} are emissions from agricultural direct and indirect energy use (in Tg CO_2-eq), subscript p is the energy type consumed during on-farm production, consisting of diesel (cost by agricultural machines) and electricity (cost by irrigation); subscript q refers to the type of agricultural materials inputs, including mineral fertilizer, pesticide, and film; and other symbols as describe above.

2.3.3 Calculations for the GHG emissions in the post-production subsector

When accounting for GHG emissions from post-production stages, an essential issue is determining the proportion of food system in each economic sector. For food processing, there are several economic sectors (e.g., food processing, food production, beverage production and tobacco processing) are 100% related to food processing and, in turn, relate to the food system. That means we could directly add their emissions as the emissions from food processing:

$$E_{\mathrm{pro}}=\sum\nolimits_{u=1}^{4}\sum\nolimits_{v=1}^{17}\mathrm{ef}_v\times\mathrm{AD}_{uv}\times\mathrm{GWP}_{\mathrm{CO_2}} \quad (10)$$

where, E_{pro} is the emission from food processing (in Tg CO_2-eq); subscript u refers to the subsector of food processing, containing food processing, food production, beverage production and tobacco processing; subscript v is the type of energy, which is consistent with Shan et al.[27]; and other symbols as described above.

For other stages in food supply chain, such as food packaging,

Table 1 Data used in the GHG emission accounting and scenario analyses in this study

Subsystem	GHG source/sink	Activity data	Parameter
Land use			
	Unchanged cropland Unchanged grassland Converted cropland, grassland and forest	LUCC maps[18] Chinese vegetation map[19] Chinese ecological zones[31]	Soil and biomass carbon densities by land-use types[21,22,29] Forest carbon sinks by species[29]
Agricultural production			
Agricultural activities	Rice cultivation Mineral fertilizer application Livestock manure application Crop straw return Enteric fermentation Manure management	Crop production[32] Crop sown area[32] Livestock number[32] Mineral fertilizer use[32]	Emission factors[23–25,33,34] Grain-straw ratios[24] Crop root-shoot ratios[24] Crop water contents[24] Crop N contents[24] Straw burning ratios[34] Straw return rates[25] Livestock manure return rates[25] Livestock excretion rates[17,35,36] Livestock slaughter periods[17,35]
Agricultural direct energy use	Diesel (consumed by machines) Electricity (consumed by irrigation)	Diesel use[32] Irrigation area[32]	Emission factors[37–39]
Agricultural indirect energy use	Mineral fertilizer production Pesticides production Film production	Mineral fertilizer use[32] Pesticides use[32] Film use[32]	(Indirect) emission factors[38,39]
Post production			
	Food processing Packaging Transport and storage Wholesale and retail Consumption	MRIO tables*[27,40] CO_2 emission inventory by economic sectors[27,40] Energy balance sheets[32] Household energy survey[41]	Emission factors[23,24,27]

Note: * In this study, we used 1997 MRIO table for accounting GHG emissions of 1992 because of lacking data. The times of GHG accountings and MRIO tables in other years are consistent.

transport and storage, wholesale and retail, GHG emission accounting is difficult. This is due the fact that MRIO tables and emission inventories only include the entire transport, storage, wholesale and retail sectors, of which the proportion attributable to food supply is unknown. On the basis of economic relationships reflected in MRIO tables, we adopted EIO-LCA method to identify the GHG emissions induced by food transport and storage, as well as food wholesale and retail.

$$\boldsymbol{E} = \boldsymbol{R}(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{Y} \tag{11}$$

$$E_{\mathrm{t\_s}} = \sum\nolimits_r e_{\mathrm{t\_s,pro},k} \tag{12}$$

$$E_{\mathrm{w\_r}} = \sum\nolimits_r e_{\mathrm{w\_r,pro},k} \tag{13}$$

$$E_{\mathrm{p}} = \sum\nolimits_r \sum\nolimits_{w=1}^{4} e_{w,\mathrm{pro},k} \tag{14}$$

where, $\boldsymbol{E}$ is the total carbon emission matrix (in Tg CO_2-eq), whose columns and row vectors represent the CO_2 emissions caused by the requirements of corresponding column sectors and the inputs of corresponding row sectors, respectively; $\boldsymbol{R}$ is the direct carbon emission intensity matrix (in Tg CO_2-eq per thousand yuan) which was derived by dividing sectoral CO_2 emissions in Shan et al.[27] by the respective total economic values in MRIO tables; $\boldsymbol{I}$ is the identity matrix; $\boldsymbol{A}$ is the direct input coefficient matrix; and $\boldsymbol{Y}$ is the diagonal matrix of final consumption derived from MRIO tables. E_{p} denotes the emission from food packaging (in Tg CO_2-eq), $E_{\mathrm{t\_s}}$ denotes the emission caused by food transport and storage sector (in Tg CO_2-eq), and $E_{\mathrm{w\_r}}$ denotes the emission caused by food wholesale and retail sector (in Tg CO_2-eq); $e_{\mathrm{t\_s,pro}}$ is the element located in the intersection of the row of transport and storage sector and the column of food processing sector in matrix $\boldsymbol{E}$, representing the emission in the transport and storage sector caused by the needs of food processing sector (in Tg CO_2-eq);

$e_{w\_r,pro}$ denotes the emission in wholesale and retail sectors caused by the needs of the food processing sector (in Tg CO_2-eq); $e_{w,pro}$ are emissions in package-related industrial sectors caused by food processing requirements (in Tg CO_2-eq); subscribe r denotes regions in MRIO tables; subscribe w are the industrials related to packaging, including paper production, chemical material production, metal production and non-metal mineral production.

Cooking-related GHG emissions were calculated for both rural and urban residents. For the rural part, we extracted national-level long-term cook used energy data from rural residential energy-mix surveys[42,43], and then distributed them to different provinces according to the annual reports on building energy efficiency in China[44,45]. For the urban part, the national-level cook energy use data were from BERC-THU[46] and Ning et al.[47], and we further distributed the energy use to a province level according to the numbers of households in different provinces[48]. The formula for GHG emissions from food consumption was:

$$E_{\mathrm{con}} = \sum\nolimits_{k=1}^{2} \sum\nolimits_{t=1}^{3} \mathrm{ef}_t \times \mathrm{AD}_k \times \mathrm{GWP}_{\mathrm{CO_2}} \qquad (15)$$

where, E_{con} denotes the GHG emission from food consumption (in Tg CO_2-eq), subscript k denotes the type of residents, namely rural and urban residents; subscript t indicates the type of fuel used in cooking, which includes coal, gas, LPG; and ef and AD are emission factors and activity data used in the calculations of cooking-related GHG emissions, with exact values and references shown in Table 1.

2.4 Scenarios setting

We designed two scenarios, namely business as usual and low-carbon scenarios, to explore the impacts of low-carbon strategies on GHG emission in the CFS in 2050 (Table 2).

2.4.1 2050 business as usual scenario

This scenario depicts a future that follows the present development pattern with high resource and environmental

Table 2 The descriptions of scenarios and the changes to corresponding activity data and parameters

Type	2050 business as usual	2050 low-carbon	Data sources
GDP and population	Both GDP and population follow the SSP2s	Both GDP and population follow the SSP1s	[49]
GDP	Increase by 308% compared to 2015	Increase by 323% compared to 2015	
Population	Decrease to 1286 million	Decrease to 1250 million	
Diet	Keep the current trend toward a fatter eating pattern	Turn to the recommendation of Chinese Nutrition Society	[50,51]
Cereals	5179 kJ (+8% compared to 2010)	3998 kJ (–16%)	
Red meat	1918 kJ (+15%)	1114 kJ (–33%)	
Poultry	268 kJ (+21%)	465 kJ (+109%)	
Milk	511 kJ (+114%)	473 kJ (+98%)	
Fruit and vegetable	779 kJ (–19%)	1214 kJ (+26%)	
Agricultural productivities	Keep unchanged	Crop productivity forecasts originate from the SSP1 results in GLOBIOM Taking the USA as a reference, pig and poultry productivities are predicted to increase by 20% over 2010. For beef cattle, dairy cattle, sheep, goats and layer, the increase rates are assumed to be 40%	[52–54]
Rice	–	6.6 t·ha^{-1}	
Wheat	–	7.6 t·ha^{-1}	
Corn	–	9.1 t·ha^{-1}	
Pork	–	110 kg per head	
Beef	–	191 kg per head	
Milk	–	10.8 t per head	
Mitigation technologies	No further measures are adopted All emission factors keep unchanged, related activity data changes in current trend	All effective activities are adopted to reduce GHG emission	–

(*Continued*)

Type	2050 business as usual	2050 low-carbon	Data sources
Agricultural inputs changed			
Nitrogen fertilizer	13% higher than 2017 (BAU scenario in cited paper)	22% lower than 2017 (4R nutrient management adopted, with enhanced organic fertilizer returning)	[55]
Phosphorus fertilizer	5% higher than 2017 (BAU and SSP2 scenarios in cited papers)	69% lower than 2017 (manure is well managed and returned to the field)	[56,57]
Potash fertilizer	19% higher than 2017 (SSP2 in cited paper)	15% higher than 2017 (SSP1 in cited paper)	[58]
Diesel	74% higher than 2017 (BAU scenario in cited paper)	44% higher than 2017 (low-carbon scenario in cited paper)	[59]
Pesticides	15% (just assumption, an average change of nitrogen and phosphorus fertilizer)	13% lower than 2017 (just assumption, an average change of nitrogen and phosphorus fertilizer)	–
Irrigation	53% higher than 2017 (BAU scenario in cited paper)	31% higher than 2017 (low-carbon scenario in cited paper)	[59]
Film	77% higher than 2017 (SSP2 scenario in cited paper)	40% higher than 2017 (SSP1 scenario in cited paper)	[55,60]
Technology & management changed			
Cropland carbon sink ability	–	120% high than current practice (mineral fertilizer + straw returning + no tillage)	[61]
Grassland carbon sink ability	–	Increase by 0.017 $ha^{-1}\cdot yr^{-1}$ CO_2-eq compared to present condition (optimizing grazing intensity)	[62]
Rice cultivation	–	–32% (off-season application of straw + mid-season draining)	[63]
Straw return ratio	–	Reach 80% (catch up with developed countries)	[55]
Manure return ratio	–	Reach 80% (catch up with developed countries)	[55]
Soil N_2O emission	–	–25% (integrated nitrogen management)	[64,65]
Enteric CH_4	–	–13% (reducing the forage-to-concentrate ratio + feed addictive)	[66]
Manure management CH_4	–	–60% (covering + manure addictives + acidification)	[67,68]
Manure management N_2O	–	–15% (manure addictives + optimizing house condition)	[66,67]
Fertilizer production	–	–44% (catch up with the emission intensity in Europe)	[69]
Diesel	–	–32% (increase mechanical efficiency + equipment alteration)	[59]
Film production	–	–38% (equipment alteration + change film production structure + new material)	[70]
Irrigation	–	–39% (increase mechanical efficiency + equipment alteration)	[59]
Straw burning ratio	–	None	–
CO_2 emission intensity in each economic sector	–	–35% (same as the decrease between 2005 and 2030)	[71]

Note: BAU, business as usual; 4R nutrient management, using right fertilizer source at the right rate, at the right time and in the right place; GLOBIOM, Global Biosphere Management Model; SSP, shared socioeconomic pathways.

cost (Table 2). Social-economic factors, mainly GDP and population, follow SSP2 (shared socioeconomic pathways 2) as defined by IIASA[49]. Considering the huge impact of food consumption on its production, we assume the Chinese diet would be characterized by a higher level of consumption. This translates to a 1.02-fold increase in monogastric livestock product consumption and a more than 50% increase in for ruminant products[50]. Crop and animal productivities, as well as their emission factors, stay at their current levels, which serve as benchmarks and enable us to identify the impacts of technology improvements by comparing these to the low carbon scenario.

2.4.2 2050 low carbon scenario

The low carbon scenario is designed to depict a sustainable future in which the nexus of socioeconomic conditions, mitigation technologies, and food system are in a virtuous circle of promotion (Table 2). National GDP and population would change in the manner predicted by SSP1, and Chinese diets would follow the recommendation of Chinese Nutrition Society[51]. We assumed that integrated technologies would increase crop and livestock productivity[52]. Large-scale mitigation measures are applied, especially advances in 4R crop management, manure management and industrial energy conservation. Specific measures and the corresponding mitigation factors are described by literature[64–68] and the National Climate Change Program[72]. In addition, the areas of forest, cropland and grassland would increase slightly according to relevant land-use plans[73,74]. The SOCs of cropland and grassland are likely to increase through organic fertilizer application, no tillage and restoration of grassland[61,62]. For more details, please refer to the FABLE Report 2020[75].

3 RESULTS AND DISCUSSION

3.1 Historical greenhouse gas emitted by the Chinese food system

The net emission of the CFS increased from 785 to 1094 Tg CO_2-eq in 1992 to 2012 and then decreased to 1080 Tg CO_2-eq in 2017. In the first two decades, agricultural activities and indirect agricultural energy use increased by about 286 Tg CO_2-eq contributing to more than 80% of the increase in GHG emissions (excluding GHG sequestrations by LULUC) in this period (Fig. 2(a)). When these two subsectors stabilized (or decreased slightly) between 2012 and 2017, the net GHG emission from the CFS also declined by 1.4%. The emission from agricultural direct energy use more than doubled during the study period, but its contribution to the GHG increase in the whole food system was less than 10%, due to its small initial emission. GHG emissions and sinks from post-production and LULUC remained stable, with changes of less than 40 Tg CO_2-eq (Fig. 2(a)).

The Sankey diagrams (Fig. 2(b)) clarify the comparison of GHG emissions in the CFS between 1992 and 2017. Mineral fertilizer application, livestock manure and crop straw application, and manure management were not only large GHG emission sources (65 to 148 Tg CO_2-eq in 2017), but they also increased at rapid rates (48% to 108%). As a result, N_2O emission increased by about 60% (Fig. 2(b)). The growth of CO_2 emissions was even stronger, with indirect CO_2 emissions from agricultural inputs soaring by 95% to 258% and the growth rate of direct CO_2 emission from diesel and irrigation also reached 142% and 38%, respectively. The CO_2 emission (sink) from post-production and LULUC subsectors were much less because the decrease in LUC emission was small compared to the unconverted LU sink, and the increased emission from food consumption was partly offset by the decrease in the emission from food packaging. In addition, rice cultivation and enteric fermentation had decreased CH_4 emission as a result of the decline of rice-sown area, beef cattle and draft livestock (Fig. 2(b)).

Historical changes in GHG emissions reflected the transition of development philosophies of the CFS. Between 1992 and 2012, the main focus of the CFS was increasing agricultural productivities, whose agricultural inputs and production increases could explain 90% of the total increased GHG. Meanwhile, GHG increased in the post-production subsector by 12%, with more frequent food transportation and dining out widely regarded as main contributors[76,77]. Environmental pollution gradually increased after the 2010s, attracting the attentions of both public and the government. Serial policies related to agriculture were launched, including an action plan for zero growth of fertilizer and pesticide use, and an another for organic substitution of mineral fertilizer, which marked the turning point toward green agriculture development in China[78–80]. For example, a small reduction in mineral fertilizer emissions halted GHG emission at both the production and application stages from 2012 to 2017 resulting in a 5-Tg CO_2-eq reduction (Fig. 2(b)). Benefiting from the strict land-use policy, the area of each type of land did not change significantly, so their abilities to sequester CO_2 were kept at a stable level of about 140 and 91 Tg CO_2-eq for grassland and cropland, respectively (Fig. 2(a)).

3.2 Spatial patterns of the greenhouse gas emission from the Chinese food system

As expected, regions in central and southern China, Sichuan, and Heilongjiang had the highest GHG emissions from agricultural activities (Fig. 3(a)). Their intensive crop and livestock production, especially the rice cultivation, makes them emit more GHG than other areas. Provinces located in East China fell into the second highest emission category, generally with less rice cultivation or fertilizer application to the highest emission areas. In grazing areas, agricultural activity emissions were relatively low, with enteric fermentation becomes the most important emission stage.

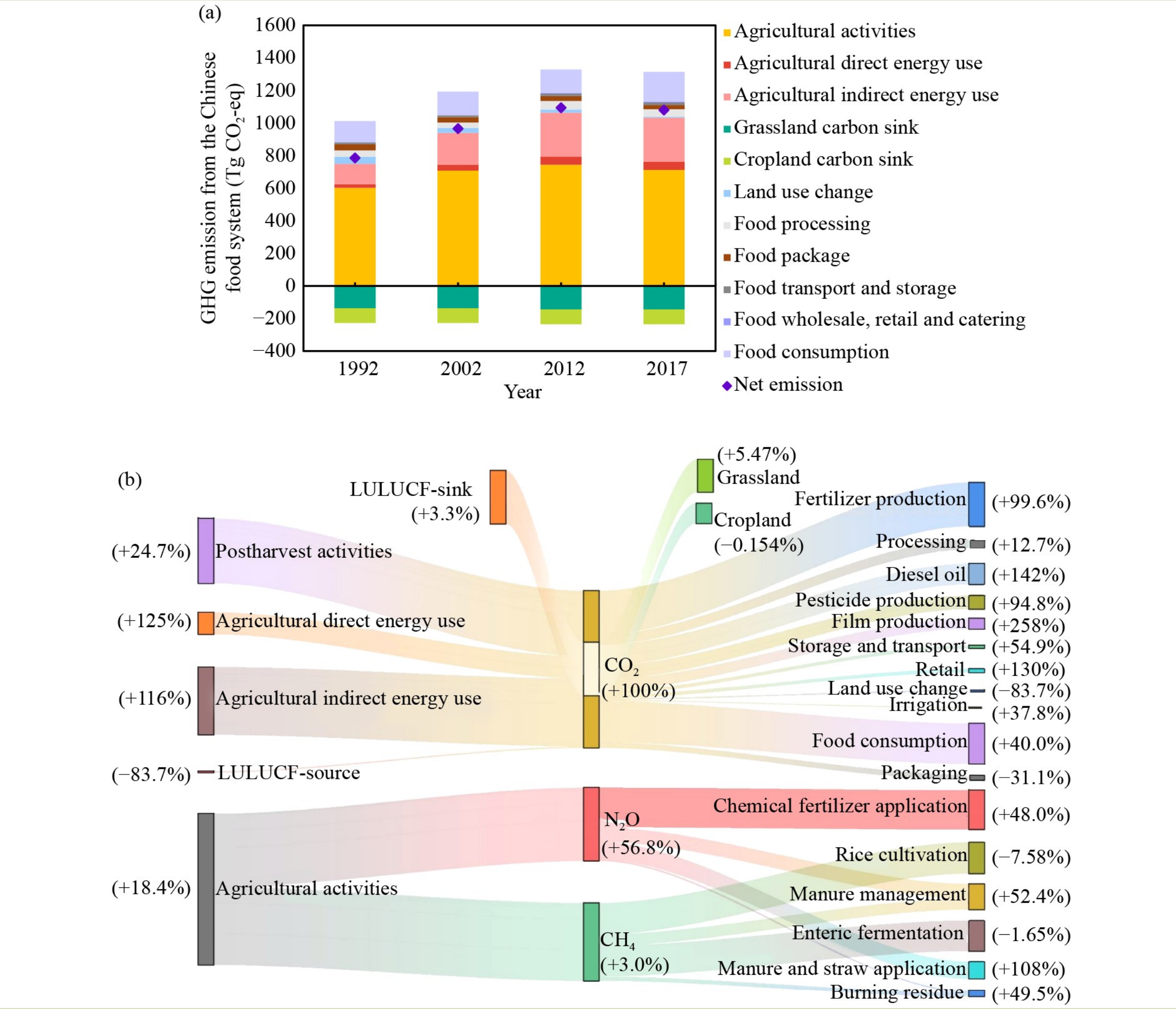

Fig. 2 GHG emissions from the CFS by sector from 1992 to 2017 (a) and the Sankey diagram illustrating the link between GHG emission sectors, gas types and stages in the CFS (b), where the percentages in parentheses are the emission change between 1992 and 2017 (b).

Also, due to the small agricultural production, Zhejiang and Fujian had low emissions from agricultural activities (Fig. 3(a)).

The spatial distribution of areas with high emissions from agricultural energy use was similar to that of agricultural activities. However, the highest emission areas shifted to the North China Plain, owing to their high consumption of fertilizer and diesel (Fig. 3(b)). Topography and economic level are likely to have been limiting factors for agricultural energy use, since mountainous regions like Guizhou, Jiangxi, Chongqing and Fujian had relatively low emissions, while Xinjiang, with flat terrain and large-scale cotton production, ranks second in terms of agricultural energy emissions. Overall, fertilizer production was the overwhelming contributor to the emissions from agricultural energy use in China (Fig. 3(b)).

Most areas with high carbon sinks are located in the west and south of China and the North China Plain. Large-scale grassland restoration actions prompted the increase of soil carbon storage in western and southern grasslands (Fig. 3(c)). However, grassland in Inner Mongolia still gave a sharp drop in soil carbon storage because of the lagged effect of degradation[21]. Soil carbon also increases steadily in the long-established agricultural areas such as the North China Plain and the Yangtze River Basin, but not in the Northeast China. This phenomenon lies in crop production and crop straw return[61] in the first two regions, as well as overgrazing and excessive cultivation in Northeast China. Additionally, cropland to grassland is the main conversion type, but with a small area compared to unconverted land, thus land-use

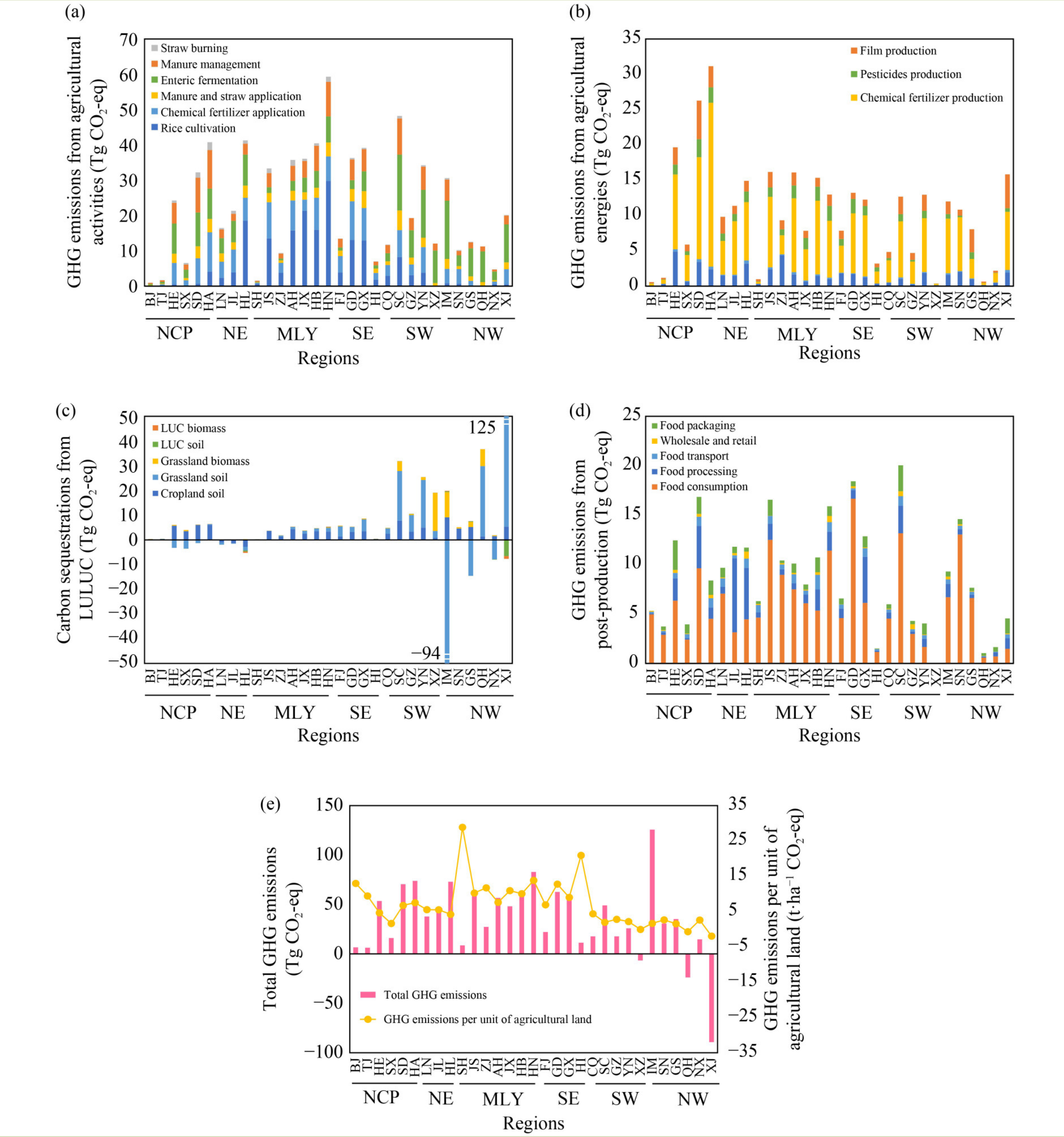

Fig. 3 Spatial distribution of greenhouse gas (GHG) emissions from agricultural activities (a), agricultural energy use (b), LULUC (land use and land-use change) as net carbon sink, with negative values representing GHG emissions and positive values representing carbon sinks (c), post-production (d), and whole food system and the emissions from the whole food production system (e) in 2017. NCP, North China Plain: BJ, Beijing; TJ, Tianjin; HE, Hebei; SX, Shanxi; SD, Shandong; HA, Henan. NE, Northeast China: LN, Liaoning; JL, Jilin; HL, Heilongjiang. MLY, middle and lower reaches of Yangtze River: SH, Shanghai; JS, Jiangsu; ZJ, Zhejiang; AH, Anhui; JX, Jiangxi; HB, Hubei; HN, Hunan. SE, Southeast China: FJ, Fujian; GD, Guangdong; GX, Guangxi; HI, Hainan. SW, Southwest China: CQ, Chongqing; SC, Sichuan; GZ, Guizhou; YN, Yunnan; XZ, Tibet. NW, Northwest China: IM, Inner Mongolia; SN, Shaanxi; GS, Gansu; QH, Qinghai; NX, Ningxia; XJ, Xinjiang.

change just acted as a weak carbon source in 2017 (Fig. 3(c)).

The spatial pattern of post-production GHG emissions was similar to that of agricultural production, despite the fact that high emission areas are more concentrated in developed regions (Fig. 3(d)). For example, Jilin, Heilongjiang, and

Guangxi, which have primary food processing industries, have relatively high CO_2 emissions. Then food consumption, as the most crucial emission source in the post-production subsector, determined whether an area was an emission hotspot. Thus, Jiangsu and Guangdong were the highest emitting provinces, whereas Yunnan and Henan were not in the list of emission hotspots. High emissions were also observed in Shaanxi and Inner Mongolia because of their rich coal sources and high proportions of energy export (Fig. 3(d)).

Finally, total GHG emissions from the CFS were found to be concentrated in central and southern China, the North China Plain and Northeast China. The above regions, accounted for 60% of total GHG emission from the CFS, were home to the five highest emitting regions. At the same time, food systems in Xinjiang, Tibet and Qinghai were shown as carbon sinks. The GHG emission structure varies throughout China (Fig. 3(e)). The main agricultural provinces in South China, for example, were primarily affected by agricultural activities (non-CO_2), whereas their counterparts in North China were affected by both agricultural activities and related industrial emission, resulting in higher CO_2 emissions. Also, more attention needs to be given to Inner Mongolia and Northeast China to stem the land degradation caused by the food system. From the perspective of emission intensity, Central China, East China, Jing-Jin region (Beijing and Tianjin) become the top areas, followed by the North China Plain (Fig. 3(e)). That reflects the fact that agricultural activities are highly intensive in Central and East China compared with their small and fragmental agricultural areas.

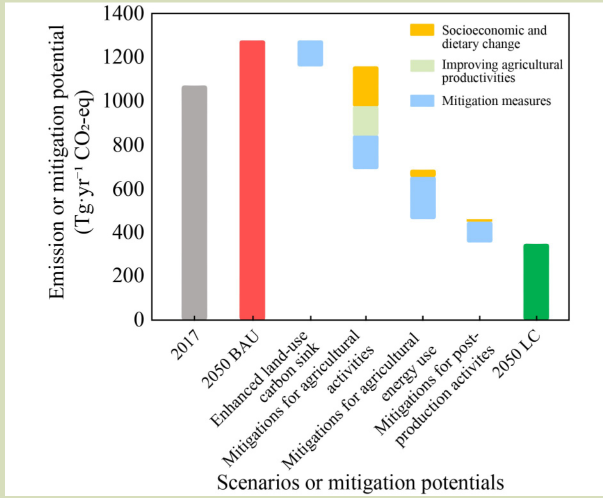

Fig. 4 Mitigation potential of different measures in the Chinese food system. 2050 BAU, 2050 business as usual scenario; 2050 LC, 2050 low-carbon scenario.

3.3 Strategies to achieve a low-carbon food system in China

Under the 2050 business as usual scenario, total emissions were predicted to reach 1285 Tg CO_2-eq, up 20% from 2017 (Fig. 4; Table 3). A higher consumption diet is thought to be a primary cause of these increased emissions. For example, the animal-related emissions, including emissions from manure application, enteric fermentation and manure management, was predicted to increase by 113 Tg CO_2-eq compared to 2017. The emissions from agricultural energy was predicted to rise to 422 Tg CO_2-eq, where diesel and agricultural film would be the

Table 3 The subsector disaggregated GHG emissions from the Chinese food system in 2017 and 2050 scenarios

Subsector	Year or scenario		
	2017 (Tg CO_2-eq)	2050 BAU (Tg CO_2-eq)	2050 LC (Tg CO_2-eq)
LULUC	−228	−227	−343 (+51%)
Agricultural activities	712	814	334 (−59%)
Agricultural energy	321	422	193 (−54%)
Post-production	274	276	171 (−38%)
Total	1079	1285	355 (−72%)

Note: 2050 BAU, 2050 business as usual scenario; 2050 LC, 2050 low-carbon scenario; LULUC, land use and land-use change. Numbers in brackets in the column of "2050 LC" denote the emission change rates between 2050 BAU and 2050 LC scenarios.

two main emission growth sources (Fig. 4; Table 3). This increase would be in line with the development of agricultural modernization in China. The increase in emissions from post-production is likely to slow because the Chinese population is predicted to decline slightly (Table 2). With the cropland lower limit and livestock production intensification, we estimated that cropland and grassland areas would remain unchanged. That, in turn would lead to stable carbon sink capabilities.

Total emissions from the CFS could be reduced to 355 Tg CO_2-eq in the 2050 low carbon scenario, which is close to the status of net zero (Fig. 4; Table 3). Agricultural activities had the highest mitigation potential at 480 Tg CO_2-eq, where the contributions of socioeconomic and dietary change, improved agricultural productivity and mitigation technologies could be 39%, 28% and 33%, respectively (Fig. 4; Table 3). In terms of emission sources, the potential would mainly be located in rice cultivation, mineral fertilizer application, enteric fermentation and manure management, exceeding 55 Tg CO_2-eq for each. Emissions from agricultural energy use were predicted to decrease by 54% compared to the 2050 business as usual scenario. As a result of improving nutrient management, fertilizer production was predicted to decrease by 135 Tg CO_2-eq and hence contribute about 60% of the emission decline in the agricultural energy use subsector. Post-production had a stable mitigation potential under the assumption of eliminating half of the food packaging and improving emissions per GDP by 35% in 2050 low carbon scenario. Considering the practice of land management (e.g., enhancing organic fertilizer return, no tillage and grassland restoration), there will be an extra 115 Tg CO_2-eq carbon sink from the LULUC subsector (Table 3).

There remains considerable uncertainty in the estimation of mitigation potential. Firstly, in our accounting model, we used some predictive values from other studies as exogenous variables. However, the assumptions underlying these predictive values are possibly different from the socioeconomic assumptions in our model, despite the fact that we screened the preconditions before using the values. Secondly, uncertainties may come from model parameters we used. For example, the carbon sequestration saturations of cropland and grassland are largely affected by the data sampling, spatial interpolation and statistical methods, thus may introduce uncertainties on the quantifications of carbon sequestration potential. Thirdly, we rescaled land-use data in agricultural ecological zone level to provincial level based on the land-use patterns shown in LULUC maps, which might not be the real situation, which adds uncertainties to our results.

Nevertheless, we still believe the CFS is capable of achieving net zero by 2050 or 2060. Given that the agricultural land is saved under the high productivity assumption, this could be converted to natural land to increase carbon sinks. Also, other measure, such as the shift from fossil fuel to electricity in energy use, could also reduce GHG emissions from the CFS.

4 CONCLUSIONS

This study developed a life cycle GHG emission accounting model for the CFS, encompassing 21 carbon sources and sinks from LULUC to agricultural production and further post-production stages. This appears to be the first study in China to build a food system GHG emission accounting model with both high sectorial and spatial resolution, providing a broader perspective on the amount and variability of GHG emissions caused by food production and consumption. The characterization of a food systems GHG model is crucial for our increased understanding of mitigation potential. Not only does it consider the mitigation potential of direct mitigation technology, but also the mitigation potential reflected in dietary changes and agricultural advances. These findings indicate several priorities for making climate policies.

Between 1992 and 2017, the net GHG emissions from the CFS increased from 785 to 1080 Tg CO_2-eq. Agricultural activities were predicted to account for more than half of the total emissions over the study period, while the agricultural energy subsector was the largest contributor to the GHG increase. In 2017, the North China Plain, Northeast China, and central and southern China had the highest levels of GHG emissions. When it comes to emission intensity, the highest emitting areas shifted to eastern China, central and southern China, and the Jing-Jin region, while carbon sinks were found in western China, such as Xinjiang, Qinghai and Tibet. Scenario analyses found that GHG emissions could be reduced to 355 Tg CO_2-eq. CO_2-eq through adjusting diet, increasing agricultural productivities and enhancing endpoint mitigation technologies. The potential for synergistic mitigation is significant for agricultural activities, where dietary changes and improving agricultural productivity could contribute over 60% of the GHG reduction from the CFS.

Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2023494 contains supplementary materials (Fig. S1; Tables S1–S2).

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Compliance with ethics guidelines

Xinpeng Jin, Xiangwen Fan, Yuanchao Hu, Zhaohai Bai, and Lin Ma declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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