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Excessive synthetic fertilizers elevate greenhouse gas emissions of smallholder-scale staple grain production in China

Yan Xu[a,b,1], Xiangbo Xu[c,d,1], Jing Li[a,c,*], Xiaoxia Guo[e,f], Huarui Gong[a], Zhu Ouyang[a], Linxiu Zhang[c,d], Erik Mathijs[g]

[a] *Yellow River Delta Modern Agricultural Engineering Laboratory, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China*
[b] *University of Chinese Academy of Sciences, Beijing, 100049, China*
[c] *Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China*
[d] *United Nations Environment Programme-International Ecosystem Management Partnership (UNEP-IEMP), Beijing 100101, China*
[e] *College of Resources and Environmental Sciences, China Agricultural University, Beijing, 100193, China*
[f] *Environmental Policy Group, Wageningen University, Hollandseweg 1, 6706 KN, Wageningen, the Netherlands*
[g] *Department of Earth and Environmental Sciences, KU Leuven, Leuven 3001, Belgium*

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ABSTRACT

Smallholder farmers produce one-third of the world's food and over 80% of China's; therefore, they must be at the forefront of developing a sustainable food system. Greenhouse gas (GHG) emissions from these farms cannot be ignored. In this study, we created an agricultural environmental impact evaluation framework for China based on a localized database through an extensive survey. The survey was based on face-to-face interviews by 120 investigators with 1015 smallholders in 100 villages within Chinese major agricultural regions. The GHG emissions of each smallholder farmer's staple grain production was assessed on a case-by-case basis. Structural equation models were used to analyze the influence paths of production behavior. The results showed that GHG emissions from smallholder grain production exceeded average global levels. Despite some regional differences, synthetic fertilizers were the main source of GHG emissions from all farm inputs. Increased farm size can reduce nitrogen fertilizer use. The GHG emissions can be reduced by 203.59–279.90 Tg CO_2eq, and profits would increase by 62.05–92.42 billion CNY in China, when all smallholders are managed in the same way as the top 25% or 10% of outstanding producers without applying higher nitrogen fertilizer application than the national recommendation. It is urgent and necessary for smallholders to change production practices to reduce their reliance on fertilizers to achieve climate goals.

1. Introduction

Reducing greenhouse gas emissions while ensuring food security is crucial for realizing the United Nations Sustainable Development Goals (SDGs). In China, 1.4 billion residents are fed by two hundred million farmers (Hou et al., 2021), who on average farm 0.5 hm^2 each (the global average is 2 hm^2) (Eisenstein, 2020); as a result, food security in China mostly relies on the contribution of smallholder farmers. Currently, challenging global food markets and losses in yield and earnings due to climate change have caused increasing pressures on smallholder livelihoods (Ricciardi et al., 2021). Based on the Paris Agreement, the Chinese government has pledged to reach peak CO_2 emissions by 2030 and achieve carbon neutrality by 2060 (Van Soest et al., 2021).

Greenhouse gas (GHG) emissions from the global food system account for approximately 30% of the total global GHG emissions, most of which come from agricultural input production, field applications, and livestock activities (Clark et al., 2020). Due to limited awareness and restricted access to technology, smallholder farmers heavily rely on chemical inputs, notably synthetic fertilizers and pesticides, to boost

* Corresponding author. Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China.

E-mail address: jingli@igsnrr.ac.cn (J. Li).

[1] These authors contributed equally to this work.

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crop yields. Developed nations have recognized the environmental consequences of excessive fertilizer usage early on. Since the 1980s, the Water Framework Directive and Nitrates Directive had been introduced in Europe, limiting fertilizer use to 170 kg N/hm^2 and providing economic incentives to encourage fertilizer reduction (Zhang et al., 2019). The United States relies on Best Management Practices to optimize fertilizer application in multiple ways. Conversely, China, with a nitrogen fertilizer usage three times higher than the global average, faces a stark imbalance: its nitrogen fertilizer use efficiency is only half, exacerbating environmental issues and contributing to a higher global warming potential (GWP) (Cui et al., 2018). In the 2000s, China phased out incentive subsidies for fertilizer purchase and production. China has also begun to take a number of measures to promote the reduction of synthetic fertilizers, including the Zero Fertilizer Use Growth Plan, Soil Testing and Formulation, and Organic Fertilizer Substitution for Synthetic Fertilizer (Hou et al., 2023). Subsidy policies have shifted towards green production, emphasizing environmental protection (Ju et al., 2016). Achieving China's climate goals requires tight collaboration with smallholder farmers; understanding their production behavior and environmental performance helps to drive changes towards a more sustainable production mode by all stakeholders.

Conducting a comprehensive evaluation of food systems and their climatic impacts presents considerable challenges (Guo et al., 2022b). Although life cycle assessment (LCA) methods are widely embraced by scholars worldwide, the complexities involved in inventorying and parameterizing emissions have led to diverse approaches for quantifying GHG emissions across various sectors (Ou et al., 2021). Official statistical data have the advantage of authoritativeness and continuity; they are the primary data source for many studies focusing on GHG emissions from food systems (Cheng et al., 2011). National statistical yearbooks and published findings have been employed to analyze the spatial and temporal distribution patterns of GHGs in rice, wheat, and maize production (Xu and Lan, 2017) and to identify key influencing factors (Chen et al., 2021). However, due to the challenges of obtaining emission parameters across diverse temporal and spatial dimensions, these results generally provide only large-level estimates. The assessment of direct emission intensity in field trials or monitoring endeavors has been utilized to gauge the environmental impact of agricultural production. GHG emissions from crop systems, exemplified by rice production in southern China (Lin et al., 2021) and wheat production in northwestern China (Kamran et al., 2023), have been assessed through static chamber and gas chromatography measurements in long-term experimental fields. This approach, constrained by economic costs and data collection difficulties, typically enables region-specific or technology-specific analyses. Recent research efforts have increasingly utilized rural farm surveys to assess GHG emissions, though the need for expanded sample sizes to achieve national representativeness remains evident (Yan et al., 2015). This study bridges the gap between the above three types of research, by integrating data from agricultural surveys of 1015 smallholders with a localized environmental impact parameter database derived from literature synthesis. Additionally, national statistics were employed to evaluate the potential for national GHG reduction. This comprehensive approach facilitates GHG assessments of the three main staple crops across China's major agricultural regions. This greatly reduced the uncertainty in GHG emission quantification.

To better analyze the impact factors other than agricultural inputs, more aspects such as climate factors, family characteristics, and socioeconomic characteristics were taken into consideration. A partial least squares structural equation model (PLS-SEM) was used to construct and verify the paths of multiple influencing factors on farmers' fertilizer-use behavior and GHG emissions. Compared with the traditional covariance-based structural equation model (CB-SEM), it has higher statistical power (especially in dealing with multicollinearity) and intuitiveness (Wei et al., 2019), which can better explore and develop path models to verify causal relationships between variables (Huang et al., 2019).

In this study, LCA was carried out based on questionnaire data from smallholder farmer surveys in the main agricultural regions of China: (1) to precisely quantify the GHG emissions of each smallholder farming system, (2) to analyze the grain production behavior and GHG emissions of smallholder farmers among different staple crop types and regions, (3) comprehensively consider socioeconomic factors and use structural equations to explore the key factors and mechanisms that affect GHG emissions and production behavior, and (4) to explore the reduction potential of GHG emissions through optimized management based on scenario analysis.

2. Materials and methods

2.1. Study area and data collection

The smallholder survey data for this study are nationally representative and based on the China Rural Development Survey (CRDS). Trained investigators conducted face-to-face interviews with more than 1015 farmers. Jilin, Hebei, Shaanxi, Sichuan and Jiangsu were randomly selected as representative provinces from the five major agricultural regions of China (northeast, southeast, southwest, northwest, and north China) (Li et al., 2021). One hundred sampling villages were identified from fifty townships in twenty-five counties, and ten households were randomly selected from each village to generate sample households (Supplementary Information, Fig. A1). The survey included planting information for each crop on the farmland (i.e., synthetic fertilizers, farmyard manure, pesticides, irrigation water, agricultural mulch, etc. Finally, we collected information on 159 pesticides and 105 chemical fertilizers, and detailed information is provided as Supplementary Information (Table B1 and B2) (Xu et al., 2023).

2.2. Greenhouse gas calculation based on LCA

The Agri-LCA model was used to assess the GHG emissions from household-scale staple crop production in China. GHG refers to the three main GWP-100 (IPCC, 2021) of CO_2, N_2O and CH_4, the results expressed in CO_2 equivalents (CO_2-eq), N_2O and CH_4 were calculated as the CO_2-eq using a 100-year time horizon. It was established based on SimaPro 9.0 and included a localized database of environmental impact parameters based on peer-reviewed Chinese research. During the process of collecting environmental impact parameters, we not only considered the differences caused by crop types but also the differences in climate and environment between North and South China; more details are provided in the Supplementary Information (Table B3–B5).

The system boundary of this study started with agricultural input production and ended with crop harvest (Fig. A2). Therefore, GHG emissions derived from both upstream production and farming activities were included in the life cycle inventory. Downstream activities, including distribution, agro-processing, consumption, and waste disposal, were excluded, and carbon sequestration in soil was also excluded according to the PAS 2050 guidelines (Yan et al., 2015). Two functional units (FU) were used: unit area (1 hm^2) and unit yield (1 kg). The time unit is one year. The life cycle inventory (LCI), a combination of all inputs and emissions from crop production, is presented in Table B6. A brief description of the cultivation management of rice, maize and wheat has been recorded as Table B7. Midpoint assessment results were performed using the ReCiPe 2016 impact assessment methodology introduced in the SimaPro 9.0 database manual, and attribution LCA was used to identify GHG emissions. The GWP-100 for N_2O and CH_4 are 298 and 34 (He et al., 2023).

2.3. Construction and validation of PLS-SEM

This study applies PLS-SEM for theoretical modelling. It consists of structural equations that describe the relationship between exogenous and endogenous latent variables, and measurement equations that describe the relationship between latent variables and observed variables. The formulas of the measurement model and the structural model are provided in equations (1) and (2), while more details (e.g., indicator selection (Table B8), model quality assessment) are recorded in the Supplementary Information.

$$x_{ij} = \Lambda_{ij}\xi_i + \delta_{ij} \tag{1}$$

In Equation (1), x_{ij} represents the vector group composed of observed variables, ξ_i represents the vector group composed of latent variables, Λ_{ij} is the factor-loading matrix of the observed variables on the latent variables representing the relationship between the observed variables and the latent variables, δ_{ij} represents the error term for the observed variable x_{ij}.

$$\xi_i = \sum_{i \neq j} \Gamma_{ij}\xi_j + \zeta_i \tag{2}$$

In Equation (2), Γ_{ij} represents the relationship between ξ_i and ξ_j and ζ_i is the residual term in the structural model and is not related to $\xi_i (i \neq j)$.

2.4. Analysis of total GHG emissions and total profits

The economic benefit analysis of grain production is based on the output obtained in the survey, with reference to the output value (Eq. A1) calculated by the National Development and Reform Commission's guidelines (NDRC, 2019) and the actual input (Eq. A2) in the survey. The calculation method (Eq. (3)) is as follows:

$$\text{Profit} = \text{Product output value-Actual input} \tag{3}$$

This study used Equations (4) and (5) to estimate the annual total GHG emissions and total profits of rice, wheat, and maize in China. The environmental and economic indicators used in the calculations were area based.

$$\text{Total GHG emissions} = \text{EI}_i \times \text{A}_i \tag{4}$$

$$\text{Total profits} = \text{P}_i \times \text{A}_i \tag{5}$$

In Equations (4) and (5), EI_i and P_i are the GHG emission and profit factor per unit area (1 hm^2) of the *i*th crop, A_i is the planting area of the *i*th crop in 2018 (Table B9), and the data comes from the National Bureau of Statistics (NBSC, 2022). The different parameters EI_i were recorded in the Eqs. A3–A6.

2.5. Scenario analysis

The pursuit of sustainable agriculture should consider both environmental concerns and economic feasibility (Guo et al., 2022a). Changing farmer behavior requires more than scientifically sound, evidence-based technologies (Cui et al., 2018). Knowledge diffusion hinges upon progressive farmers assuming leadership roles, guiding fellow villagers. Consequently, accomplished producers serve as exemplars, advocating optimal management practices in line with national fertilizer recommendations. In this study, we use greenhouse gas (GHG) emissions and economic profits to represent environmental and economic performance. Surveyed producers achieving lower GHG emissions and superior economic profits were defined outstanding producers. In this study, we adopt GHG emissions and economic profits as representatives of environmental and economic performance, respectively and detailed information is provided as Supplementary Information. Accordingly, six scenarios (S) were proposed based on the situation in 2018. Specifically, S0 is the baseline scenario, representing the current average production level of smallholder farmers. S1 assumed that staple crop production achieved the management level of the top 25% of outstanding producers. S2 assumed that staple crop production achieved the management level of the top 10% of the outstanding producers. S3 assumed that staple crop production achieved the average recommended level of nitrogen fertilizer application proposed by the national agricultural sector (MOA, 2013). S4 and 5 assumed integrated fertilizer reduction and optimized management (achieving both the management level of the top 25% or 10% of outstanding producers and the recommended fertilizer application level).

3. Results and discussions

3.1. Input, output and GHG emissions of the grain production

According to the survey, the grain production area cultivated by smallholder farmers was relatively small. The average planting areas of rice, wheat, and maize were 0.33 ± 0.56, 0.55 ± 0.82, and 0.67 ± 1.08 hm^2, respectively (Table 1), which was far less than the global average (2 hm^2). Meanwhile, farmlands showed high fragmentation, exceeding 9.67 plots/hm^2. The yield was maintained at 8033.66 ± 1678.98 kg/hm^2, 6071.34 ± 1297.00 kg/hm^2, and 6644.79 ± 2608.12 kg/hm^2 for rice, wheat, and maize, respectively. The average input amount of synthetic fertilizers exceeded 250.90 ± 195.35 kg N/hm^2, which was 31.58% higher than the amount (190 kg N/hm^2) recommended by the Chinese Ministry of Agriculture, and the use of pesticides exceeded 1.34 ± 1.51 scalar kg/hm^2. The average irrigation water consumption exceeded 274.35 ± 689.91 m^3/hm^2 and the highest was for wheat (774.74 ± 1213.47 m^3/hm^2). Mechanization was measured by oil use, with an average of more than 27.82 ± 33.09 fuel kg/hm^2 and the highest used was for wheat: 58.94 ± 26.28 kg/hm^2. The average input of agricultural films was exceeded for maize and rice at 6.32 kg/hm^2 and 12.01 kg/hm^2, respectively. Whereas, almost no agricultural film was used in wheat production. The profit of rice was 2017.69 ± 1100.89 CNY/hm^2 and 0.25 ± 0.16 CNY/kg, the profit of wheat was 987.99 ± 834.90 CNY/hm^2 and 0.15 ± 0.13 CNY/kg, and the profit of maize was 1126.94 ± 1081.78 CNY/hm^2 and 0.15 ± 0.20 CNY/kg.

From the perspective of planting area (Fig. 1a), the GHG emissions of rice, wheat and maize are 12989.80 ± 3131.56 $kgCO_2eq/hm^2$, 4327.23 ± 1836.24 $kgCO_2eq/hm^2$, 3864.26 ± 2335.71 $kgCO_2eq/hm^2$, and the yield based GHG emissions were 1.67 ± 0.51 $kgCO_2eq/kg$, 0.76 ± 0.42 $kgCO_2eq/kg$, and 0.71 ± 0.64 $kgCO_2eq/kg$, respectively (Fig. 1b). The GHG emissions after decomposition in the production process of rice were, the farming process made up 78.66%, of which 47.82% was field methane emission, followed by the N_2O emission of urea (14.86%), and the farming process of other inputs accounted for 0.05–11.92%. The proportion of agricultural input production (i.e., fertilizers, pesticides, agricultural film, etc.) ranged from 0.02% to 11.35% (Fig. 1d). Emissions for rice according to agricultural inputs are as follows: the highest contribution coming from synthetic fertilizers (48.58%), including compound fertilizers (CF), urea, etc., followed by field methane emissions (47.82%). Other agricultural materials account for 0.02–0.50%, and energy input accounted for 1.91%. The upstream production process of agricultural inputs accounted for 62.36% and 65.60% of the GHG emissions in wheat and maize production, respectively. The largest contributor to GHG emissions in wheat production was CF (32.43%), followed by the field emission of urea (15.21%) (Fig. 1e). The agricultural input was made up of CF (47.58%), followed by urea (27.94%), other fertilizers (0.04–4.50%), other agricultural materials (0.48–4.73%), and energy input (8.32%). The highest contribution to the GHG emissions of maize production was CF (39.99%), followed by field emissions of CF (19.30%). Production processes of other agricultural inputs accounted for 0.02−12.74% of GHG emissions, and other farming activities accounted for 0.01−15.15% of GHG emissions (Fig. 1f). The agricultural input accounted for CF (59.29%), followed by urea (18.35%), other fertilizers (0.83–8.54%), other agricultural materials (0.48–4.73%), and energy input (4.04%). Synthetic fertilizers, represented by CF and urea, are the most important contributors to crop GHG emissions, more than 54.06% of the total. The GHG emission contribution of each production process showed similar results when calculated per unit area and unit output.

Table 1
Production overview and agricultural inputs of major staple grain production.

	Rice (n = 266)		Wheat (n = 271)		Maize (n = 539)	
	Mean	SD	Mean	SD	Mean	SD
Planting area (hm^2)	0.33	0.56	0.55	0.82	0.67	1.08
Yield (kg/hm^2)	8033.66	1678.98	6071.35	1297	6644.79	2608.12
Fragmentation [1]	17.19	16.29	9.67	8.29	17.27	26.26
The usage of synthetic fertilizer ($kg\ N/hm^2$)	324.56	199.1	292.54	150.83	250.9	195.35
The usage of farmyard manure ($kg\ N/hm^2$)	28.32	97.27	3.61	11.38	63.32	203.81
Irrigation water (m^3/hm^2)	342.29	659.35	774.74	1213.47	274.35	689.91
Use of machinery (fuel kg/hm^2)	47.14	47.67	58.94	26.28	27.82	33.09
Agricultural film (kg/hm^2)	12.01	27.83	0	0	6.32	18.94
Pesticide (scalar kg/hm^2)	1.63	1.88	1.34	1.51	1.92	2.94

[1] Fragmentation: Fragmentation = N_i/A_i, N_i is the number of land plots, and A_i is the total planting area.

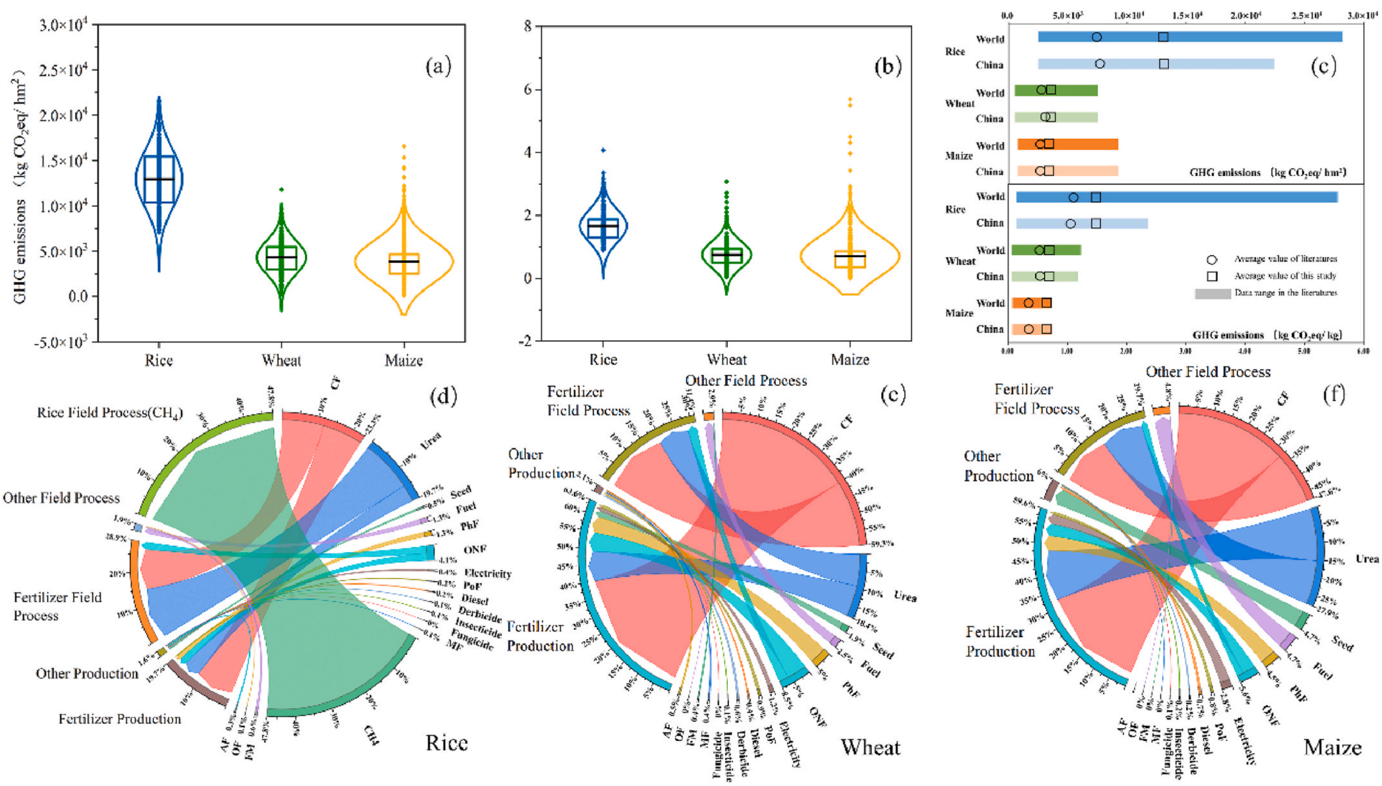

Fig. 1. Basic overview of major staple grain production. (a) GHG emissions per unit area of different staple grains; (b) GHG emissions per unit yield of different staple grains; (c) Comparison of GHG emissions between national and global level; (d) Production process decomposition of rice GHG emissions; (e) Production process decomposition of wheat GHG emissions; (f) Production process decomposition of maize GHG emissions.

The GHG emissions reported in the literature are shown in Fig. 1c, and the details are listed in Table B10. The average intensity of global GHG emissions from the three crops reported in other studies were 7862 $kgCO_2eq/hm^2$ and 1.23 $kgCO_2eq/kg$ (rice), 2611 $kgCO_2eq/hm^2$ and 0.55 $kgCO_2eq/kg$ (wheat), 2402 $kgCO_2eq/hm^2$ and 0.34 $kgCO_2eq/kg$ (maize). The average intensity of national GHG emissions from the three crops were 7068 $kgCO_2eq/hm^2$ and 1.05 $kgCO_2eq/kg$ (rice), 3006 $kgCO_2eq/hm^2$ and 0.51 $kgCO_2eq/kg$ (wheat), 2486 $kgCO_2eq/hm^2$ and 0.37 $kgCO_2eq/kg$ (maize). It is noteworthy that GHG emissions at the smallholder farmer level in this study exceeded both global and China's average emission levels, with disparities of 35.81%–83.78%. The emission intensity for wheat closely resembled that reported by Yan et al. (2015) from a similar smallholder survey conducted in this study. However, both rice and maize exhibited significantly higher emission intensities, measuring 116.50% and 68.01% higher, respectively. This divergence may also be attributed to the use of nitrogen fertilizer, as the fertilizer application reported in this study was close to theirs for wheat, but 20.65% and 50.46% higher for rice and maize. Given that nitrogen fertilizer accounts for more than 50% of GHG emissions, the excessive use of nitrogen fertilizer by smallholder farmers contributes to the elevated emission intensities observed. This underscores the importance of implementing measures to mitigate emissions.

3.2. Staple grain production and GHG emissions vary among different regions

More than 75.76% of China's smallholder farmers' rice planting area is less than 0.3 hm^2, and fragmentation exceeds 7.71 plots/hm^2. Jiangsu and Jilin had the largest average smallholder rice planting area, both exceeding 0.42 hm^2, while that in Sichuan and Shaanxi was less than 0.15 hm^2; but the degree of fragmentation was the highest in Sichuan (25.88 plots/hm^2). The yield varied from 700 to 16,000 kg/hm^2, with an average of more than 8848.73 kg/hm^2 in Jiangsu, followed by Sichuan and Jilin. In terms of synthetic fertilizer input, the highest amount was used in Jiangsu (390.46 kg N/hm^2), while the lowest amount used was in Jilin (187.95 kg N/hm^2), but the level of farmyard manure usage was the highest in Sichuan (49.06 kg N/hm^2) and Shaanxi (147.95 kg N/hm^2). Irrigation and agricultural machinery use are also the highest in Jiangsu (725.35 m^3/hm^2 and 75.64 kg fuel/hm^2), while agricultural film (5.47 kg/hm^2) and pesticide (1.23 scalar kg/hm^2) use are lower (Table A1).

The GHG emission of rice production in Shannxi Province was the highest, with an average of 15047.12 ± 4792.37 $kgCO_2eq/hm^2$, followed by Jiangsu and Sichuan, whereas Jilin had the lowest GHG emission (10293.86 ± 2301.87 $kgCO_2eq/hm^2$), which accounts for only 68.41% of that in Shannxi (Fig. 2a). Comparing the GHG emissions of the production process in Shannxi and Jilin, the urea (production and field process) emissions were different almost by a factor of five (1904.54 and 527.7 $kgCO_2eq/hm^2$), other nitrogen fertilizer (field process) emissions were different almost by a factor of fifteen (1265.63 and 82.96 $kgCO_2eq/hm^2$), and the difference in their usage of synthetic fertilizers almost determined their GHG emissions (Fig. 2d). In terms of unit yield, Shannxi reached 2.07 ± 0.67 $kgCO_2eq/kg$, while other provinces were 1.48–1.71 $kgCO_2eq/kg$ (Fig. 2g). The emission of other nitrogen fertilizers except for CF and urea in Shaanxi was almost double that of other provinces, up to 0.37 $kgCO_2eq/kg$, resulting in its overall high GHG emission (Fig. 2h).

The wheat planting area in different regions varies mostly between

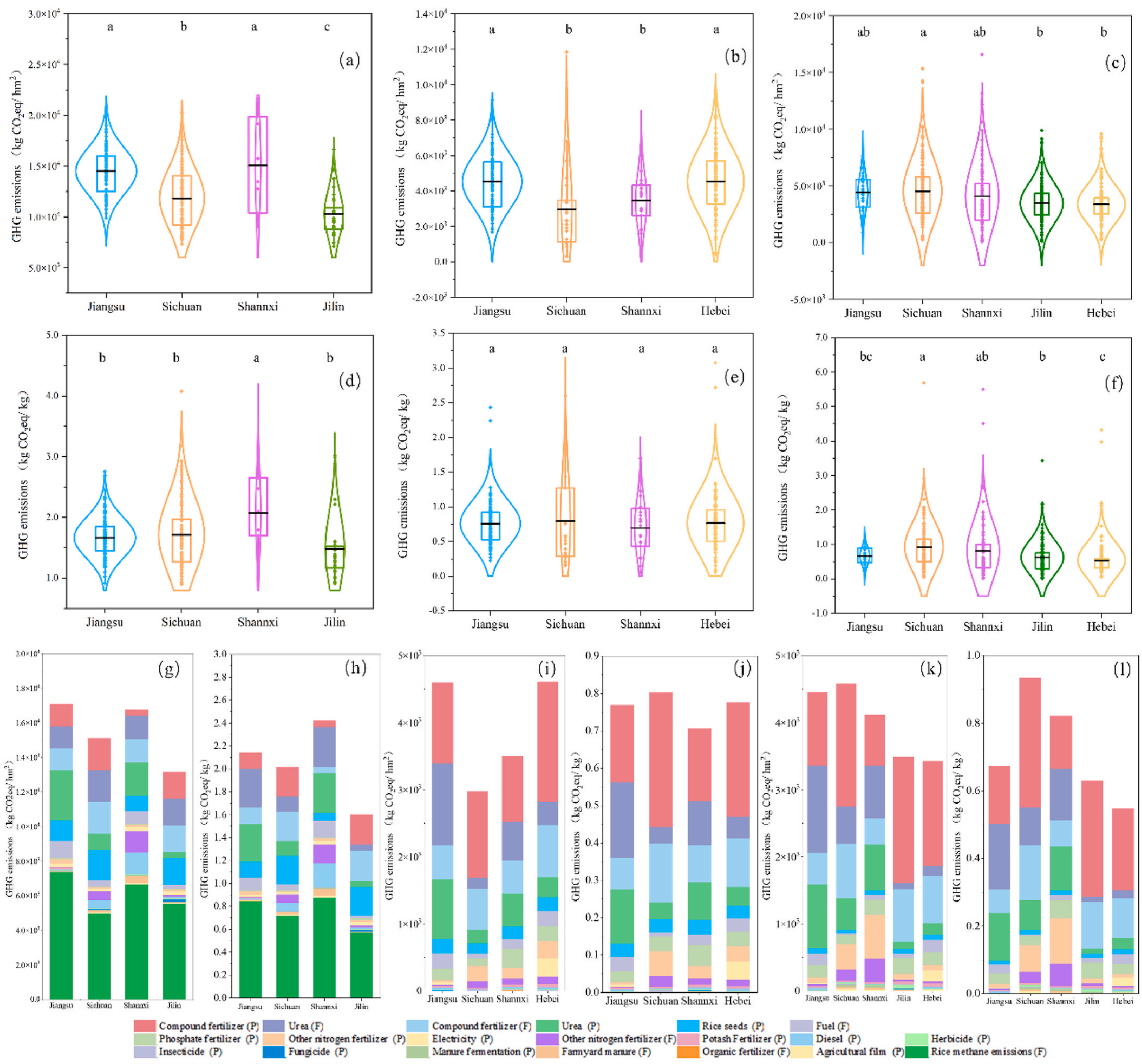

Fig. 2. GHG emissions from staple grain production and the contribution of each production process. (a) GHG emissions per unit area of rice; (b) GHG emissions per unit area of wheat; (c) GHG emissions per unit area of maize; (d) GHG emissions per unit yield of rice; (e) GHG emissions per unit yield of wheat; (f) GHG emissions per unit yield of maize; (g) Production process decomposition of GHG emissions per unit area of rice; (h) Production process decomposition of GHG emissions per unit yield of rice; (i) Production process decomposition of GHG emissions per unit area of wheat; (j) Production process decomposition of GHG emissions per unit yield of wheat; (k) Production process decomposition of GHG emissions per unit area of maize; (l) Production process decomposition of GHG emissions per unit yield of maize.

0.1 and 0.5 hm^2, with the largest average area in Hebei (0.63 hm^2), and only 0.22 hm^2 in Sichuan, but the degree of fragmentation was the highest (21.37 plots/hm^2) in Sichuan. The yields ranged from 2250 to 12,000 kg/hm^2, with the highest yields in Jiangsu and Hebei, with an average of over 6200 kg/hm^2, followed by Sichuan and Shaanxi. Jiangsu also had the highest input of synthetic fertilizers, exceeding 361.51 kg N/hm^2, followed by Hebei (255.42 kg N/hm^2), and Sichuan was only 176.12 kg N/hm^2, but Sichuan had more than 2.99 scalar kg/hm^2 of pesticide application. A few growers in Sichuan and Shaanxi chose additional irrigation, but the irrigation in Hebei exceeds 1685.28 m^3/hm^2. None of the surveyed farmers had used agricultural films (Table A2).

Wheat production in Jiangsu and Hebei had the highest GHG emissions, with an average of more than 4528.60 $kgCO_2eq/hm^2$, while those in Shaanxi and Sichuan have an average of less than 3457.05 $kgCO_2eq/hm^2$ (Fig. 2b). The emission caused by urea in Jiangsu Province was the highest, with an average of 2101.63 $kgCO_2eq/hm^2$, and that in Sichuan was only 360.88 $kgCO_2eq/hm^2$, while the compound fertilizer emission in Hebei exceeded 2568.66 $kgCO_2eq/hm^2$, and the electricity emission is also much higher than other provinces (269.84 $kgCO_2eq/hm^2$) (Fig. 2i). In terms of unit yield, the differences in GHG emissions in different regions were also not significant, with an average of 0.70–0.77 kg CO_2eq/kg (Fig. 2e), but the emissions of various production processes were not consistent. Jiangsu, Shaanxi, and Hebei have the highest urea emissions, with an average of more than 0.29 kg CO_2eq/kg, while Sichuan has the highest emissions from compound fertilizer production, with an average of 0.52 kg CO_2eq/kg, which is related to the lower wheat yield in Sichuan (5589.29 kg/hm^2) than in other provinces (average 6071.35 kg/hm^2) (Fig. 2j).

More than 50% of China's smallholder farmers' maize planting area is less than 0.2 hm^2, Jilin Province has the largest average area (1.61 hm^2), while Sichuan has only 0.14 hm^2, but its fragmentation degree is the highest (38.50 plots/hm^2). Yields range from 750 to 15,000 kg/hm^2, with the highest yield in Hebei, with an average of over 7273.39 kg/hm^2, followed by Jiangsu and Jilin. The input amount of synthetic fertilizers in Jiangsu was also the highest, exceeding 375.71 kg N/hm^2, and the lowest was Jilin (191.53 kg N/hm^2) and Hebei (184.53 kg N/hm^2), but the pesticide's usage in Jilin exceeds 3.69 scalar kg/hm^2. The degree of mechanization was highest in Jiangsu and Hebei, exceeding 50.29 fuel kg/hm^2. Growers in Sichuan and Shaanxi rarely choose to irrigate, but those in Hebei irrigate more than 974.00 m^3/hm^2. The maximum amounts of agricultural film used in Sichuan and Hebei exceeded 6.88 kg/hm^2 (Table A3).

The GHG emissions of maize production in Sichuan were the highest, with an average of more than 4549.40 $kgCO_2eq/hm^2$, while the maize emissions in Jilin and Hebei were lower than 3467.98 $kgCO_2eq/hm^2$ on average (Fig. 2c). Urea production in Jiangsu province has the highest emissions with an average of 2253.84 $kgCO_2eq/hm^2$, Sichuan is 1028.23 $kgCO_2eq/hm^2$, and CF production in Sichuan emits more than 2636.03 $kgCO_2eq/hm^2$. Although the CF in Jilin and Hebei exceed 2667.32 $kgCO_2eq/hm^2$, urea did not exceed 306.96 $kgCO_2eq/hm^2$ (Fig. 2k). In terms of unit yield (Fig. 2f), Sichuan also has the highest carbon emissions, with an average of 0.92 $kgCO_2eq$/kg, and the lowest in Hebei, with an average of 0.54 $kgCO_2eq$/kg. The difference between the two in farming process emissions and the synthetic fertilizer production process was more than double (Fig. 2l).

3.3. Difference in GHG emissions between farmers with different fertilization habits

Smallholder farmers were divided into those who use only synthetic fertilizers (OF) and those who use farmyard manure (M). The grain planting area of M farmers is generally smaller than that of OF farmers, which is reflected in the fact that the area planted with maize is significantly lower by 66.05% (0.27 hm^2 in M and 0.81 hm^2 in OF), while the degree of fragmentation of wheat and maize production is 34.36% and 69.35% higher, respectively. The amount of synthetic fertilizer applied by M farmers was higher than that of OF farmers, among which the amount of wheat production was 18.13% higher (330.91 kg/hm^2 in M and 280.13 kg/hm^2 in OF) and the amount of maize production was 30.78% higher (303.91 kg/hm^2 in M and 232.38 kg/hm^2 in OF). The use of wheat production machinery was 12.05% lower (53.41 kg/hm^2 in M and 60.73 kg/hm^2 in OF) and maize production was 45.37% lower (17.23 kg/hm^2 in M and 31.54 kg/hm^2 in OF). The difference in agricultural inputs did not cause a difference in output, and the yield of the major staple grains of two types of farmers was almost the same (Table A4).

In rice production, the GHG emissions (14339.15 $kgCO_2eq/hm^2$ and 1.79 $kgCO_2eq$/kg) of M farmers are more than 10% higher than those of OF farmers (12365.83 $kgCO_2eq/hm^2$ and 1.61 $kgCO_2eq$/kg), and the difference in emissions was caused by the large increase in manure and straw emissions (487.17 $kgCO_2eq/hm^2$) under the condition of rice flooding and anaerobic conditions, the urea emission is 493.65 $kgCO_2eq/hm^2$ higher, and there is no significant difference in other processes. The GHG emissions per unit area of maize production were more than 23.06% higher for M farmers (4288.00 $kgCO_2eq/hm^2$) than for OF farmers (3484.41 $kgCO_2eq/hm^2$). Compound fertilizer and urea contributed to almost all the increase, and the difference in the application of synthetic fertilizers caused an increase in GHG emissions (Fig A3).

3.4. The factors and pathways affecting the production behavior

The results of the LCA assessment showed that the production and field application of synthetic fertilizers are the most important factors affecting GHG emissions from crops. The structural model was used to explore the effects of various factors on nitrogen fertilizer use in crop production (Fig. 3). The validation results of the model showed that all model evaluation indices, including Cronbach's α, Composite reliability (CR), and the extracted average variance (AVE), were within the standard range, indicating that the measurement model was valid and reliable (Table A5). R^2 and Q^2 of nitrogen fertilizer use and farm variables were greater than 0.25, 0.22 and greater than 0.24, and 0.16, respectively. The model had a GOF value of 0.42, indicating a moderate explanatory and predictive ability of the model for nitrogen use and farm variables.

The effect of climate on farm size (both total acreage and area per plot) was stronger (−0.53) than socioeconomic factors (0.30). This is because that flat land is better for increasing farm size, and northern China (such as Jilin and Hebei provinces) has more plains than southern China. (Liu et al., 2021). Influenced by the monsoon climate, China's average temperature gradually decreases from south to north, and precipitation gradually decreases from east to west, thus also affecting China's agricultural zoning (Pan et al., 2023). The south is dominated by hills (such as Sichuan and Jiangsu provinces), where the population is dense and the cultivated land is highly fragmented. Socioeconomic factors (including subsidy factors, economic development level, etc.) have played a positive role in promoting farm scale. A developed economy can promote land transfer and improve the level of intensive farm management (such as Jiangsu province) (Han et al., 2021). The influence of farm household factors was not obvious.

Climatic factors, household, other inputs, and socioeconomic factors had positive effects on nitrogen fertilizer application, while farm size factors had negative effects. The direct effect of climate on nitrogen fertilizer use accounted for 76.85%. The climate in most parts of China is characterized by simultaneous heat and precipitation. Higher precipitation and temperature will intensify soil processes and leaching, resulting in lower fertilizer use efficiency, and farmers tend to rely on applying more fertilizer to maintain high soil fertility in the plow layer and high yield (Bai et al., 2019), which is more obvious in the Jiangsu province. The frost-free period is affected by water, heat, and altitude; therefore, the higher the altitude, the more unfavorable farmland

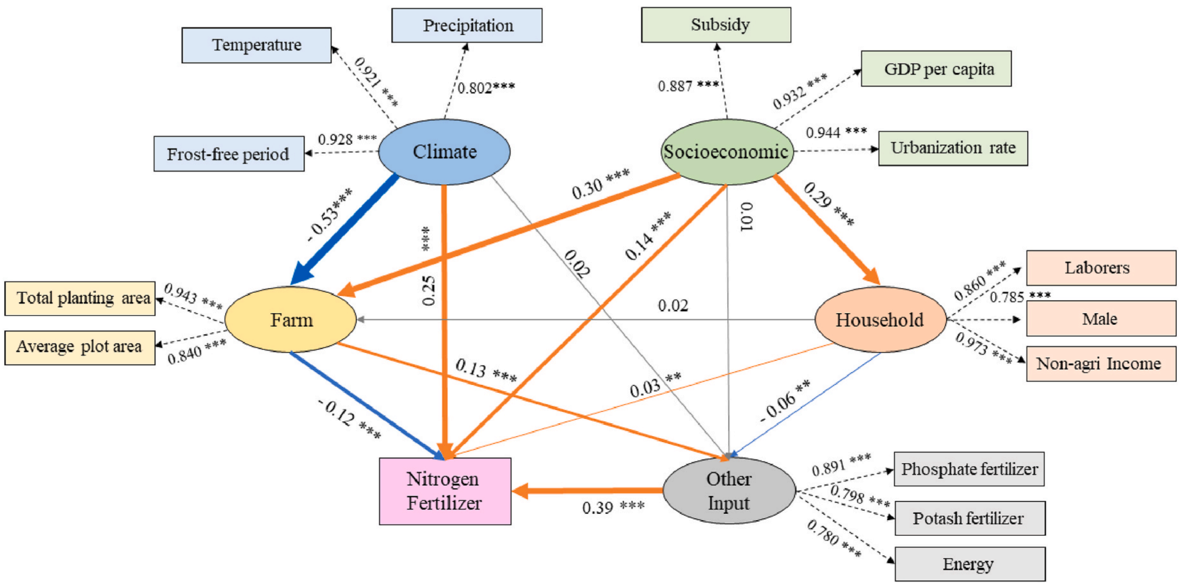

Fig. 3. The PLS-SEM pathway for the impact mechanism of smallholder production behavior. (Significance level *0.01, **0.005, ***0.001).

conditions are and require more fertilizer. However, the effect of natural factors on fertilizer-use behavior is complex, and it affects the yield more indirectly. The effect of climate on other inputs was not significant. Farm factors were negatively correlated with nitrogen application, and numerous studies have obtained similar conclusions (Ren et al., 2021). Households with larger land areas were more dependent on agricultural income, driving them to adopt advanced nutrient management techniques that are also conducive to a higher degree of mechanization (Hu et al., 2019). Therefore, the increase in the scale of farmland will correspondingly increase the input of phosphorus fertilizer, potash fertilizer and energy including diesel. On the contrary, farmers with fewer fields often need other sources of income; therefore, they only tend to consider simple agricultural inputs, especially nitrogen fertilizers.

Household characteristics also reflected farmers' consideration of fertilizer use, but the overall effect was weak (0.005), and the direct effect only accounted for 52.80%. The larger the farming labor force, the higher the proportion of males, indicating that farmers focus on agricultural output, and thus have a higher pursuit of yield. They often choose to increase nitrogen fertilizer input (Zhang et al., 2017). The higher the non-agricultural income, the lower its dependence on agriculture, the more reasonable agricultural material input will be considered to obtain the best profit. This has also been verified in other farmer household surveys (Ren et al., 2021), which proved that low ratios of fixed inputs (i.e., machinery and knowledge) to total inputs are a key factor leading to over-use of fertilizers by smallholder farmers. In terms of socioeconomic factors, a large part of China's current subsidies was used for agricultural inputs and other expenses of grain production, which means that subsidies increase scale rather than efficiency (Han et al., 2021). In most regions (such as Shaanxi, Hebei province), synthetic fertilizers and their GHG emissions have not been decoupled from economic development. However, studies also showed that decoupling has been achieved in the developed regions of eastern China (such as Jiangsu province); that is, economic development will have a negative effect on agricultural inputs such as synthetic fertilizers, and it will achieve efficiency improvements (Han et al., 2021).

3.5. Potential of agriculture GHG reductions in China

Among the surveyed smallholder farmers, we screened out the outstanding farmers, who have reduced the input of synthetic fertilizers (especially nitrogen fertilizers) and consider environmental and economic benefits as the future development directions, as representatives. The classification of producers for different crop production is shown in Fig. 4a–c, and detailed production information for different scenarios is presented in Table A6. One thing these farmers have in common is that they use less nitrogen fertilizer (38.87%–66.54% less than the average), which also means lower nitrogen fertilizer use, and production still is sustainable.

In 2018, China's agricultural GHG and crop production emissions were approximately 8700 Tg CO_2eq, and 1538.20 Tg CO_2eq, respectively (Chen et al., 2021). According to the estimation of the present study, the emission of the three major staple grains is 667.64 Tg CO_2eq (S0), accounting for about 7.67% of the emission of the agricultural system, which cannot be ignored, and has a large space for emission reduction and profit improvement (Fig. 4 d, e). When farmland management reaches the level of outstanding farmers (S1, S2), the annual GHG emissions of staple grain production can be reduced by 171.75–266.84 Tg CO_2eq, a reduction of 29.30–45.52%, and farmers' income can be increased by 65.89–91.06 billion CNY. After realizing the reduction of nitrogen fertilizer (S3), the GHG emissions can be reduced by 196.36 Tg CO_2eq, and the profit will increase by 7.36%. After realizing comprehensive production optimization (S4, S5), GHG emissions can be reduced by 203.59–279.90 Tg CO_2eq, with a maximum reduction ratio of 47.75%; profits can be increased by 62.05–92.42 billion, with a maximum increase rate of 72.73%. In the optimal scenario, it can reduce GHG emissions by 279.90 Tg CO_2eq and increase profits by 92.42 billion CNY. The potential for sustainable production is well established, and the agricultural practices of reducing nitrogen fertilizer should be widely promoted.

Hence, the recommendation for reducing fertilizer usage in this study aligns with the national guidelines, which advocate a reduction by 32.05% from the current levels, aiming to attain a target of 190 kg N/hm^2. Ideally, a more substantial reduction of 67.45% from the current levels, aiming for 94.19 kg N/hm^2, is desirable (S5). The national recommendation serves as the authoritative benchmark and has been endorsed in numerous analogous studies. For instance, Zhang et al. (2016a) proposed a reduction of 37.4% in N fertilization in accordance with the national recommendation. Furthermore, drawing from the nitrogen use efficiency (NUE) response equation, Huang and Tang (2010) recommended that achieving an NUE of 50% (equivalent to 120–150 kg N/hm^2) would result in a significant reduction in GHG emissions from crop production. Additionally, national-level relationships between yield, protein content, and nutrient efficiency have been established to elucidate the specific nitrogen fertilizer requirements for different crops,

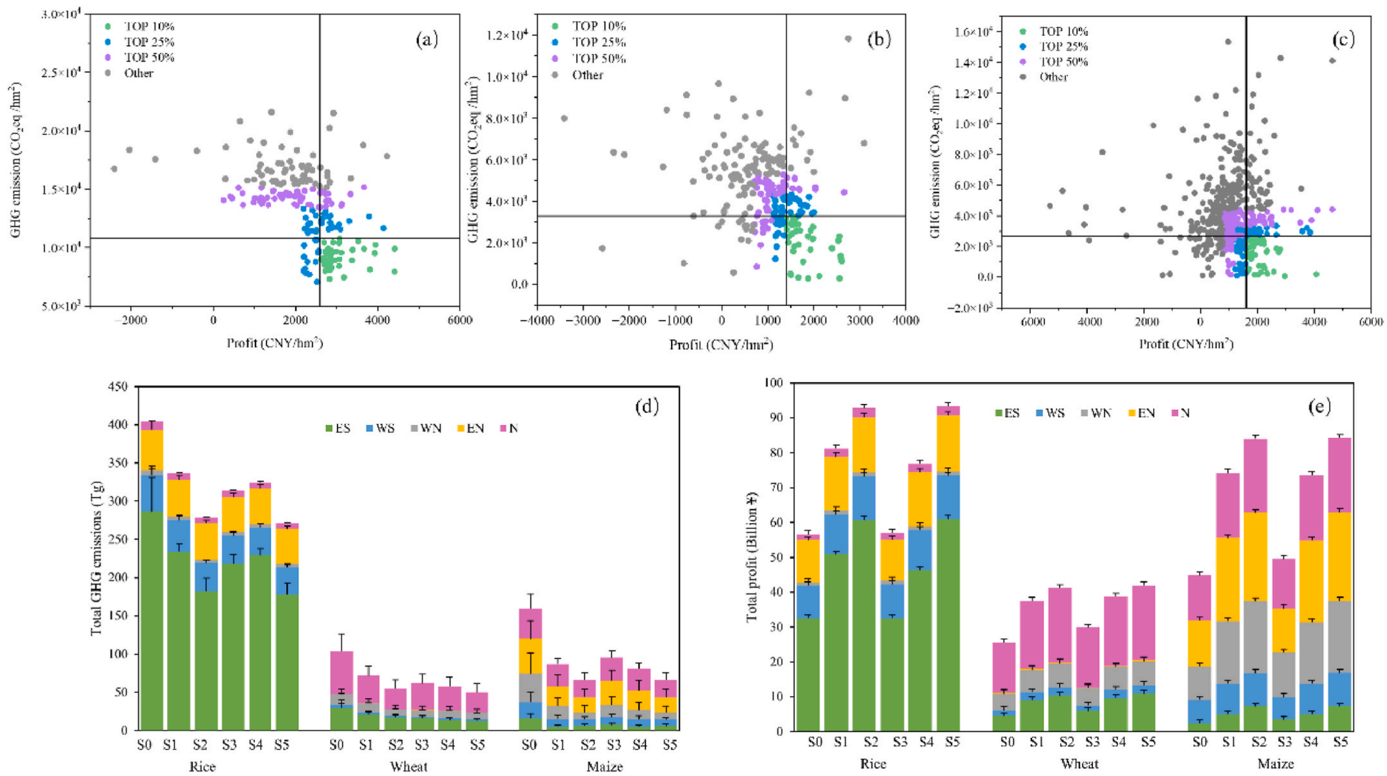

Fig. 4. Outstanding farmer's selection and scenario analysis of the three major staple grains. (a) Outstanding farmer's selection of rice; (b) Outstanding farmer's selection of wheat; (c) Outstanding farmer's selection of maize; (d) Total GHG emissions under different scenarios; (e) Total profits under different scenarios. Note: ES (South East China), WS (South West China), WN (North West China), EN (North East China), N (North China).

as demonstrated by Hou et al. (2023).

3.6. How can synthetic fertilizer reductions be achieved?

We must be aware that factors that have a positive impact on the intensity of nitrogen fertilizer use will hinder the reduction of synthetic fertilizers, and measures must be taken to reduce the persistence of smallholder farmers in the use of synthetic fertilizers. The results of this study (Fig. 5) and other studies have revealed that once crop demand thresholds are reached, GHG emissions increase exponentially with little or no additional yield gain as fertilizer-use increases (Wu et al., 2021). Proper nutrient management of crops is a priority for reducing GHG emissions. Replacing synthetic nitrogen fertilizers with livestock manure offers several advantages, encompassing enhanced crop productivity, reduced GHG emissions (Xia et al., 2017), and amplified soil biodiversity (Du et al., 2020). It was observed that substituting a portion of synthetic fertilizers with manure led to a noteworthy 6.6% and 3.3% boost in yield for dryland crops and paddy rice, respectively (Zhang et al., 2020b). This substitution exhibited no discernible influence on N_2O and CH_4 emissions from dryland crops. However, it was associated with heightened CH_4 emissions from rice, ranging from 48% to 82%. Considering a scenario where manure replaces 50% of synthetic fertilizers, equivalent to 95–125 kg N/hm^2, a substantial 15 Tg of manure would be necessitated for the national cropland. This quantity is roughly equivalent to the present national livestock excretion (Zhang et al., 2019). It is noteworthy that livestock production currently occupies an extensive 84 million hectares (Mhm^2) of cropland, inclusive of imported feed, constituting a substantial 51% of the total national cropland area (Fang et al., 2023). Consequently, the integration of crop and livestock production assumes particular significance.

The slow- and control-release N fertilizers need to be developed to enhance N use efficiency. The addition of controlled-release urea (mixed 1:1 with conventional urea) reduced GHG by 8–13% without affecting yields (Yao et al., 2021). Additionally, the use of biochar-fertilizer blends exhibits the potential to reduce greenhouse gas emissions by over 20% in wheat-maize systems (Bai et al., 2023). Precision management of crop practices, soil conditions, fertilizer application, and irrigation can curtail nitrogen fertilizer inputs and N_2O emissions. In paddy fields, deeper nitrogen fertilizer placement and no-tillage practices led to a 36–39% reduction in soil CH_4 emissions and a 29–31% decrease in N_2O emissions (Liu et al., 2020). Optimizing irrigation and fertilization, such as mid-season flooding with 180 kg N/hm^2, can lower greenhouse gas emissions by 12.3% (Liang et al., 2023). Mechanized farm management improvements (Ren et al., 2021) also enhance nitrogen fertilizer efficiency. These strategies collectively offer promise for enhancing nitrogen utilization efficiency while mitigating GHG emissions in agriculture.

The Chinese government has taken a series of actions to promote sustainable agriculture, such as the coupling of crop and livestock production, soil testing, and formulas for precise fertilization. Technological innovation requires strong policy and economic incentives. Converting subsidies for agricultural materials into subsidies and cost-sharing programs that help farmers use advanced technologies and tools may increase their confidence (Stuart et al., 2014). Some surveys have argued that informal facilitators (i.e., farmers' relatives and acquaintances) are more influential than formal facilitators (i.e., governments and businesses) (Qi et al., 2021). In recent years, the government has partnered with universities to establish research bases in villages to facilitate on-site assistance, a unique form of support provided by the "Science and Technology Backyard" (Zhang et al., 2020a). Making smallholder farmers aware of the economic and environmental benefits brought about by technological progress and improving environmental awareness requires policy making and implementation and technical innovation and transfer by the government, scientific institutions, and enterprises (Zhang et al., 2016b). More important is the "bottom-up" transformation of farmers' groups into an agricultural system with high

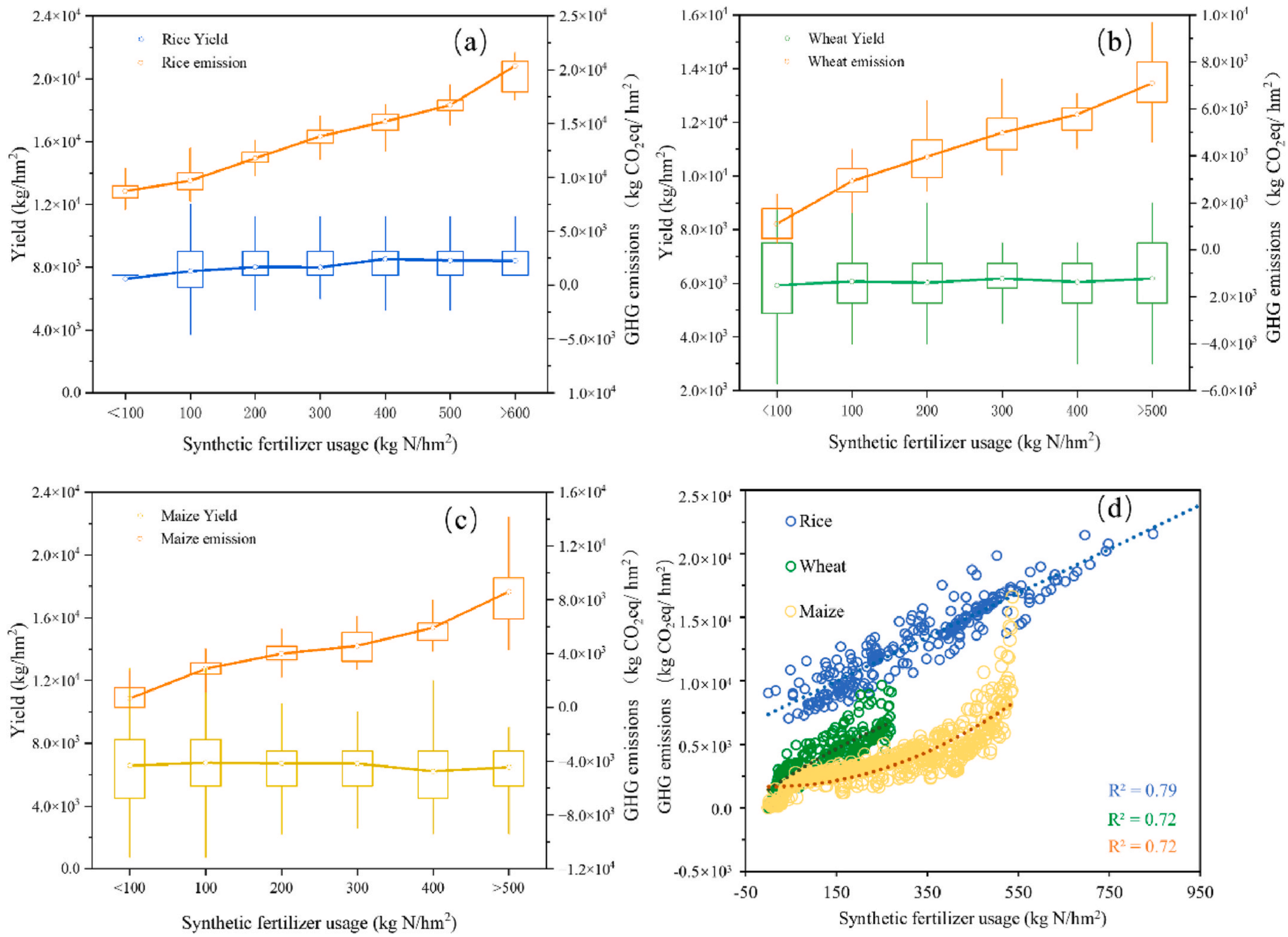

Fig. 5. The comparison between synthetic fertilizer application and yield and GHG emissions of the three major staple grains. (a) The comparison between synthetic fertilizer application and yield and GHG emissions of rice; (b) The comparison between synthetic fertilizer application and yield and GHG emissions of wheat; (c) The comparison between synthetic fertilizer application and yield and GHG emissions of maize; (d) The comparison between synthetic fertilizer application and GHG emissions of the three major staple grains.

productivity and resource utilization efficiency (Shen et al., 2013). Although this requires constant adjustment and advancement, it is the only way to achieve sustainable food production.

3.7. Uncertainty and limitation

The results of the sensitivity analysis are shown in Table A7, which shows the impact of the coefficient changes of the input factors on the results. For 12 possible input parameters, such as methane in rice production, when it varies by ±10%, the result does not vary by more than 5%, which means that the robustness is very good. Monte Carlo simulations are widely used to assess the uncertainty of LCA (Ewertowska et al., 2017). The sample size of the Monte Carlo simulation in this study is 5000. The average value of the simulation results is 12989.80 $kgCO_2eq/hm^2$, 4327.23 $kgCO_2eq/hm^2$, 3864.26 $kgCO_2eq/hm^2$ (rice, wheat, maize), and the confidence interval is 95% (11933.63–14093.63 $kgCO_2eq/hm^2$, 4189.48–4459.07 $kgCO_2eq/hm^2$, 3741.54–3993.78 $kgCO_2eq/hm^2$) (Fig. A4). The coefficient of variation (4.9%, 1.59%, 1.67%) is less than 5%, and the uncertainty of the calculated results is very low.

This study adopted the principle of stratified random sampling to reduce sampling errors and conduct professional training for investigators, and a four-round inspection of the results to reduce measurement errors. To reduce the uncertainty of the model and coefficient database for LCA analysis, we collected a coefficient database conforming to the current situation in China, based on paddy fields and upland fields, and performed separate accounting for each farmer. GHG emissions are often influenced by a combination of factors, such as climate, soil, and farming practices, and additional spatial data and emission factors are required to enhance the assessment of crop production. These factors must undergo refinement in light of extensive monitoring networks covering various agricultural areas and environmental conditions, especially when extending the perspective to provincial, regional, and national levels. Spatial heterogeneity in data variability may introduce uncertainty in the results in these broader contexts (Xu et al., 2022).

In addition, owing to the difficulty of data collection at the farmer level, we did not include the soil carbon sequestration of straw and manure disposal in the accounting process. Returning straw to the field can reduce straw burning and replace nitrogen fertilizers, which can be used as a strategy to reduce GHG emissions (Liu et al., 2018). It is worth noting, however, that organic amendments, including straw and manure, are believed to increase methane emissions from rice paddies (Guo et al., 2017). When considering rice residues, they should be managed differently, such as for use as livestock feed. Farmers' fertilizer usage is influenced by various factors, and the structural equation model established in this study considered the primary aspects of these factors; therefore, the results are preliminary. Due to limitations in sample size, this study combined the behaviors of all producers to enhance the model's stability. In the future, different regions, crops, and other influencing factors merit further analysis.

4. Conclusion

Grain production at the level of smallholder farmers in China was conducted in relatively small areas (less than 0.67 hm^2 on average) while the yields are considerable (6071.34 kg/hm^2 on average). The application of synthetic fertilizers, particularly nitrogen fertilizers, greatly exceeds the recommended amounts in the agricultural sector, which also leads to excessive GHG emissions. The GHG emissions of rice, wheat, and maize production were 12,989.80 ± 3131.56, 4327.23 ± 1836.24, and 3864.26 ± 2335.71 $kgCO_2eq/hm^2$ on a unit area basis, respectively; and 1.67 ± 0.51, 0.76 ± 0.42, and 0.71 ± 0.64 $kgCO_2eq$/kg on a unit yield basis, respectively, which all exceed the global and Chinese agricultural averages. There are certain differences in GHG emissions from different grain productions in different regions, but in general, synthetic fertilizers contributed the most to GHG emissions in grain production. Climatic, household, other inputs, and socioeconomic factors had positive effects on nitrogen fertilizer application, while farm size factors had negative effects. Shifting policies and economic incentives toward improving smallholder farmers' knowledge and skills in advanced agricultural management may reduce their use of synthetic fertilizers and promote low-carbon sustainable food production. The total GHG emissions can be reduced by 47.75%, and the total profit can be increased by 72.73% in China, when all smallholders are managed in the same way as the top 10% of outstanding producers without applying higher nitrogen fertilizer application than the national recommendation.

The study's theoretical significance lies in the development of a comprehensive LCA framework, characterized by its robust integration of localized data and parameters. This framework was applied alongside a survey involving 1015 smallholders in key Chinese agricultural regions, aiming to elucidate GHG emissions in smallholder-scale staple grain production. The research fills some gaps: firstly, addressing the limitations of national GHG emission estimates (Cheng et al., 2011); secondly, overcoming challenges tied to scaling field measurements (Lin et al., 2021); and thirdly, expanding upon smallholder-focused studies (Yan et al., 2015). Regarding fertilizer use, the study recommends a 32.05% reduction from current levels to align with the national recommended rate of 190 kg N/hm^2, in line with Zhang et al. (2016c). It also suggests that achieving the level of outstanding farmers, a 67.45% fertilizer reduction, could lead to a significant reduction of 279.90 Tg CO_2eq in GHG emissions and an increase of 92.42 billion CNY in profits within China. These findings extend beyond this research, empowering smallholder farmers and providing a scientific basis for policy and action in various developing nations, including China. Ultimately, this work contributes substantially to emissions reduction and the sustainable development of food systems.

CRediT authorship contribution statement

Yan Xu: Methodology, Writing – original draft, Data curation. **Xiangbo Xu:** Conceptualization, Writing – review & editing, Supervision. **Jing Li:** Conceptualization, Writing – review & editing, Supervision. **Xiaoxia Guo:** Validation, Formal analysis. **Huarui Gong:** Validation, Formal analysis. **Zhu Ouyang:** Validation, Formal analysis. **Linxiu Zhang:** Validation, Formal analysis. **Erik Mathijs:** Validation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.139720.

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