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RESEARCH ARTICLE

TOWARD SUSTAINABLE MAIZE PRODUCTION FOR SMALLHOLDERS THROUGH OPTIMIZED STRATEGIES IN NORTH CHINA

Jie YAN*[1], Yize LIU*[1], Rui ZHANG[1], Chenhui CUI[1], Yingying ZHENG (✉)[2], Minghao ZHUANG (✉)[1]

1 College of Resources and Environmental Sciences, National Academy of Agriculture Green Development, Key Laboratory of Plant-Soil Interactions, Ministry of Education, China Agricultural University, Beijing 100193, China.
2 College of Information and Electrical Engineering, China Agricultural University, Beijing 100193, China.

*These authors contribute equally to the work

KEYWORDS

localized optimization strategies, smallholders production systems, sustainability assessment, technical innovations

HIGHLIGHTS

- County-level sustainability assessment of maize production is presented.
- County-level improvement potential exhibits a large spatial heterogeneity.
- Promoting technical innovations can facilitate China's agricultural transition.

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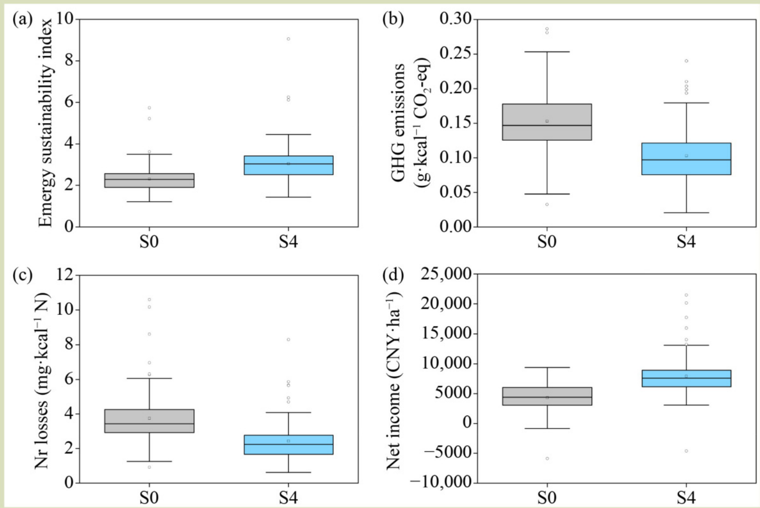
Correspondences: yyzheng@cau.edu.cn, zhuangminghao@cau.edu.cn

GRAPHICAL ABSTRACT



ABSTRACT

Agricultural production by smallholders is crucial for ensuring food provision in China. However, smallholders face a series of challenges on their farms including high-to-excess resource inputs, low use efficiency, as well as negative environmental impacts, which may be unfavorable for sustainable agriculture production. This study developed a county-level sustainability assessment of maize production in Hebei, China, by applying multiple data sources in combination with emergy, carbon footprint, nitrogen footprint and cost-benefit analyses. Scenario analysis was applied to explore the localized implementation strategies to achieve the sustainable farming system. The results show that the average emergy sustainability index (ESI) of maize at 2.31 is relatively low. The average greenhouse gas (GHG) emissions and reactive nitrogen (Nr) losses are 0.15 g·kcal^{-1} CO_2-eq and 3.75 mg·kcal^{-1} N, respectively. The average cost and net income are 12,700 and 4340 CNY·ha^{-1},

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respectively. These results indicate a great potential to improve the environmental-economic sustainability of the maize production system of smallholders. In addition, the environmental and economic indicators calculated from the maize production show a substantial spatial heterogeneity among counties, indicating a requirement for different optimization strategies to improve the environment-economy sustainability at a finer scale. Based on the multiple scenario analysis, optimal strategies targeting each county are proposed. By adopting the optimal strategies, the average ESI and net income could increase by 32% and 83%, respectively, and the average GHG emissions and Nr losses reduce by 33% and 35%, respectively. These findings provide an important reference for adopting different strategies to achieve environment-economy sustainability for smallholders production systems with diverse landscapes in North China and propose a transition pathway toward achieving agriculture sustainability for smallholders worldwide.

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1 INTRODUCTION

In China, crop production is conducted on 203 million smallholdings (~98% of all kinds of agricultural production enterprises)[1] with an average farm size of ~0.52 ha, so this system is important role in ensuring food security. However, the high resource inputs and low resource use efficiency of smallholders production systems, and the overuse of nitrogen fertilizer, cause significant negative impacts on the environment, including air pollution, soil degradation, eutrophication and resource scarcity[2–5]. Meanwhile, the negative environmental impacts jeopardize the long-term sustainability of China’s food production[6,7]. There is an urgent need to transform smallholders production systems in China.

The transformation toward sustainable smallholders production systems must address many challenges. First, fragmented farmland and decentralized management severely hinder the development of agricultural mechanization and digital/precision agriculture[8]. Gu et al. found the low ratio of mechanization is one of the key constraints leading to over-fertilization in smallholders production systems[9]. Second, with increasing urbanization, the workforce transferring to secondary and tertiary industries, and population aging in the rural areas, the available of agricultural workforce is decreasing and the cost of labor is increasing[10–12]. Young people attracted by cities are more likely to embrace new technologies while most of the aging population remaining in rural areas are not well-educated. Third, due to the large variation in resource endowment, climatic and socioeconomic conditions of smallholder production systems, selecting suitable technologies requires localized strategies[13,14], while most of the previous assessments are at national or provincial levels[15–18]. To address these challenges, localized strategies are needed but remain undefined.

In this study, we used maize production in North China as an example to explore the transformation pathway. North China Plain, one of China’s main grain production regions, contributes to nearly a quarter of the national grain output[19]. To be specific, we comprehensively evaluated the status quo of county-level sustainability assessment using emergy, carbon footprint, nitrogen footprint, and cost-benefit analyses. Then, we explored the improvement potential by closing yield or efficiency gaps, and based on this analysis discuss possible solutions for sustainable maize production for smallholders.

2 MATERIALS AND METHODS

2.1 Data sources

In this study, the sources of data include statistics yearbooks, government reports, previous publications, and a nationwide survey conducted from 2005 to 2014[13,14]. Details of data sources are shown in Table 1.

2.2 Emergy analysis

Emergy is the total amount of available energy directly or indirectly required for the production of products or services[30]. All components are converted into solar emjoules (sej) by unit emergy values with the baseline at 12.0 × 10^{24} sej·yr^{-1}[31]. All inputs of the maize production system in

Table 1 Data sources

Source	References
County-level crop yield, chemical N, P and K application rates, and manure type and its application rate	[13,14]
Meteorological data	[20–22]
Irrigating water	[23]
Pesticide	[16]
Labor, seed and plastic mulch	[24]
Electricity, diesel, gasoline and coal	[24–26]
Mechanical equipment	[27,28]
Top soil losses	[29]

our study were divided into four categories: free renewable resources (including solar energy, wind energy, rainfall and geothermal heat), free nonrenewable resources (mainly referring to the net loss of topsoil), purchased renewable resources (including irrigating water, manure, human labor and seeds) and purchased nonrenewable resources (including mineral fertilizer, electricity, fuels, mechanical equipment, pesticides and plastic mulch). The output of the system considers grains, excluding byproducts such as straw. The major emergy flows are shown in Fig. 1(a) and indicators used in Table 2.

2.3 Carbon footprint

The carbon footprint analysis of maize from cradle to farmgate includes direct and indirect greenhouse gas (GHG) emissions, such as the on-site soil N_2O emissions from nitrogen fertilizer and other GHG emissions for fuels used, and upstream emissions from the supply chain of fertilizers, pesticides, plastic mulch, seeds and electricity. The system boundary is shown in Fig. 1(b). The carbon footprint is calculated as:

$$CF = CF_{\text{input}} + CF_{N_2O} \tag{1}$$

$$CF = \sum_i Q_i \times EF_C + F_N \times EF_{N_2O} \times 44/28 \times 265 \tag{2}$$

where, CF is the total GHG emissions for each county expressed as CO_2 emissions equivalent (kg CO_2-eq), CF_{input} is the GHG emissions caused by the agricultural inputs, CF_{N_2O} is the on-site soil N_2O emissions, i are agricultural inputs, Q_i is the application rate of agricultural inputs (kg or kWh) and EF_C are their corresponding emission factors, F_N is the nitrogen fertilizer application rate (kg), EF_{N_2O} is the emission factor of soil N_2O emissions (kg·kg^{-1} CO_2-eq), and 44/28 is the molecular ratio of N_2O to nitrogen. N_2O is converted to CO_2 equivalent (CO_2-eq) according to IPCC AR5 100 year Global Warming Potential (265 times).

2.4 Nitrogen footprint

The nitrogen inputs in this study include chemical nitrogen fertilizer, manure, straw, biological nitrogen fixation, atmospheric nitrogen deposition, and seeds. The reactive nitrogen (Nr) losses include both direct and indirect losses. The direct losses in farmland mainly include NH_3 volatilization, N_2O and NO_x emissions, nitrogen leaching and runoff during the application of chemical nitrogen fertilizer and manure, NH_3 volatilization, NO_x emissions caused by straw combustion, and N_2O emissions from straw returning to the field. The indirect losses are mainly from the upstream production and transportation of agricultural inputs, such as mineral fertilizers, manure, electricity, fuels, pesticides and plastic mulch. The nitrogen flow for this analysis is shown in Fig. 1(c). The nitrogen footprint is calculated as:

$$\begin{aligned} \text{NF} = &\sum_i Q_i \times EF_N + NF_{NH_3} + NF_{N_2O} + NF_{NO_x} + NF_{\text{leaching}} \\ &+ NF_{\text{runoff}} + NF_{\text{straw burning}} + NF_{\text{straw returning}} \end{aligned} \tag{3}$$

where, i are agricultural inputs, Q_i is the application rate of agricultural inputs (kg), EF_N are their corresponding emission factors, NF_{NH_3}, NF_{N_2O}, NF_{NO_x}, NF_{leaching}, NF_{runoff} are the Nr losses in the form of NH_3 volatilization, N_2O and NO_x emissions, nitrogen leaching and runoff during the application of nitrogen fertilizer and manure, $NF_{\text{straw burning}}$ is to the NH_3 volatilization and NO_x emissions of straw combustion, and $NF_{\text{straw returning}}$ is the N_2O emissions from straw returning.

2.5 Cost-benefit analysis

Combined with the cost-benefit data[24] of maize production in Hebei Province in 2012, the cost and the net income per unit area of maize production were calculated. The total cost includes fertilizers, fuels, pesticides, plastic films, electricity, seeds, machinery, human labor and land cost (Fig. 1(d)).

2.6 Scenario analysis

An earlier study found that yield, nitrogen fertilizer and phosphorus fertilizer were the main drivers of the sustainability of staple food crops in China[13], and closing yield and nutrient use efficiency gaps could improve the sustainability and reduce negative environmental impacts[13,14]. Therefore, four scenarios were applied to explore the improving potential for ESI, GHG emissions, Nr losses, and net income for maize. Baseline (S0) was the status quo; the first scenario (S1) was for all the farmland producing the highest 10% yield in each county; the second scenario (S2) was for highest 10% in crop N efficiency at each county; the third scenario (S3) was for simultaneously highest 10% in both crop yield and N efficiency through multiplying top 32% yield by highest 32% N fertilizer efficiency at each county.

3 RESULTS

3.1 The status quo of sustainability of maize production

3.1.1 Emergy analysis

The higher the crop ESI values, the stronger the sustainability of the production system (in a range from 1 to 10) would be. The ESI values ranged from 1.2 to 5.7, with an average of 2.3, indicating that there was a great potential to improve the sustainability of the maize production system in Hebei Province. The average of the upper quartile 25% (5.7–2.6), interquartile range (< 2.6–1.9) and lower quartile (< 1.9–1.2) of ESI were 3.1, 2.3 and 1.7, respectively. The upper quartile of the counties, which is attributed to the high yield and low environmental pressure (Fig. 2(a,b)), were mainly located in the south (Fig. 2(c)). The lower quartile of the counties had a scattered distribution (e.g., Qian'an City, Quyang County, Wangdu County, Nangong City and Guangping County), mainly due to the relatively high inputs of both mineral fertilizer and fuel resulting in high environmental loading (Fig. 2(b)). The interquartile range counties were concentrated in the north of Hebei Province.

3.1.2 Carbon footprint

The distribution of the carbon footprint of maize production is shown in Fig. 2. The GHG emissions per unit area of maize production ranged from 0.72 to 6.66 t·ha^{-1} CO_2-eq, with an average value of 3.40 t·ha^{-1} CO_2-eq. The emission hotspots were concentrated in the east (Fig. 2(d)). Mineral fertilizer input was the largest contributor in 111 counties, accounting

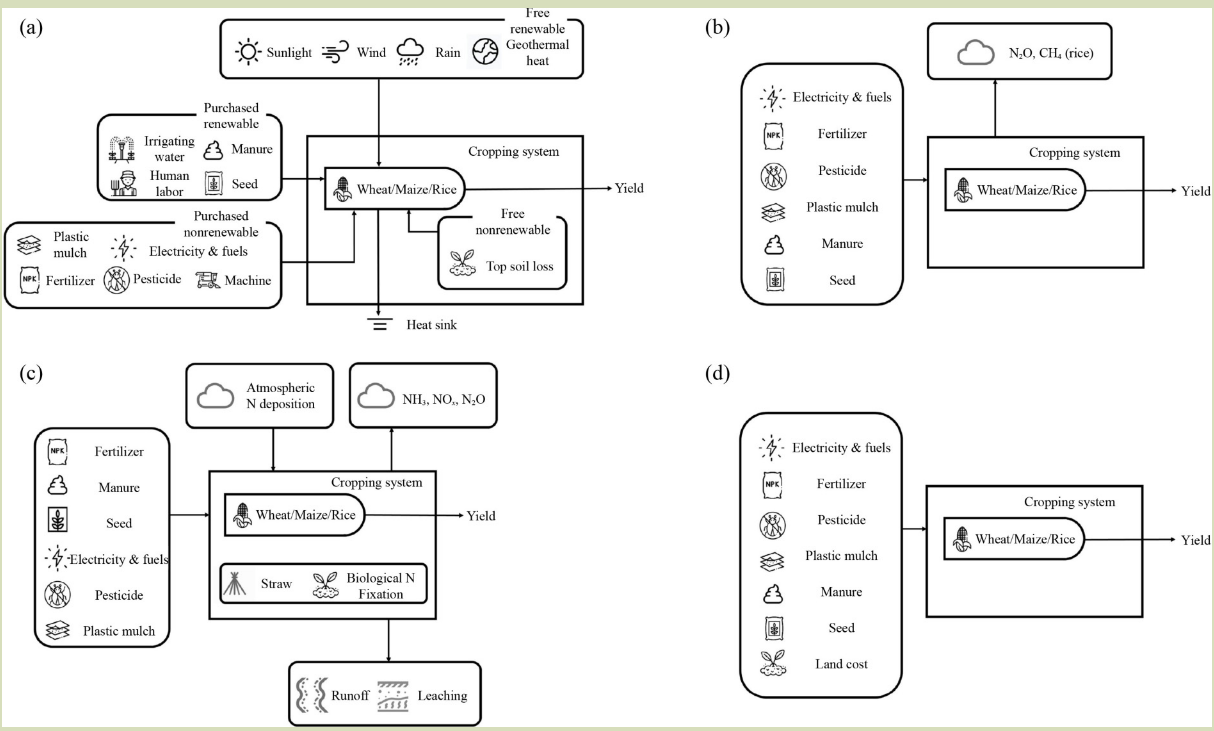

Fig. 1 System diagram for the emergy analysis (a), carbon footprint (b), nitrogen footprint (c), and cost-benefit (d) analysis.

Table 2 Emergy indicators

Emergy indicators	Formula	Meaning
Emergy yield ratio (EYR)	Y/(PR + PN)	Efficiency of purchased resource investments
Environmental loading ratio (ELR)	(FN + PN)/(FR + PR)	Environmental pressure on regional eco-economic system
Emergy sustainability index (ESI)	EYR/ELR	System sustainability

Note: Y, total system output; PR, purchased renewable resources; PN, purchased nonrenewable resources; FN, free nonrenewable resources; and FR, free renewable resources.

for more than 50% of the total GHG intensity per unit area. Taking Guangping County as an example, the high application rates of nitrogen fertilizer were more than twice of average provincial level (468 vs 202 kg·ha^{-1}).

The GHG emissions per unit calorie of maize production ranged from 0.03 to 0.29 g·kcal^{-1}, with an average of 0.15 g·kcal^{-1} CO_2-eq. The GHG emission hotspots were concentrated in the east and the south-west (e.g., Kuancheng, Manchu Nationality Autonomous County, Qian'an City and Wu'an city) due to the relatively high application rates of nitrogen fertilizer. The northern and central regions in Hebei

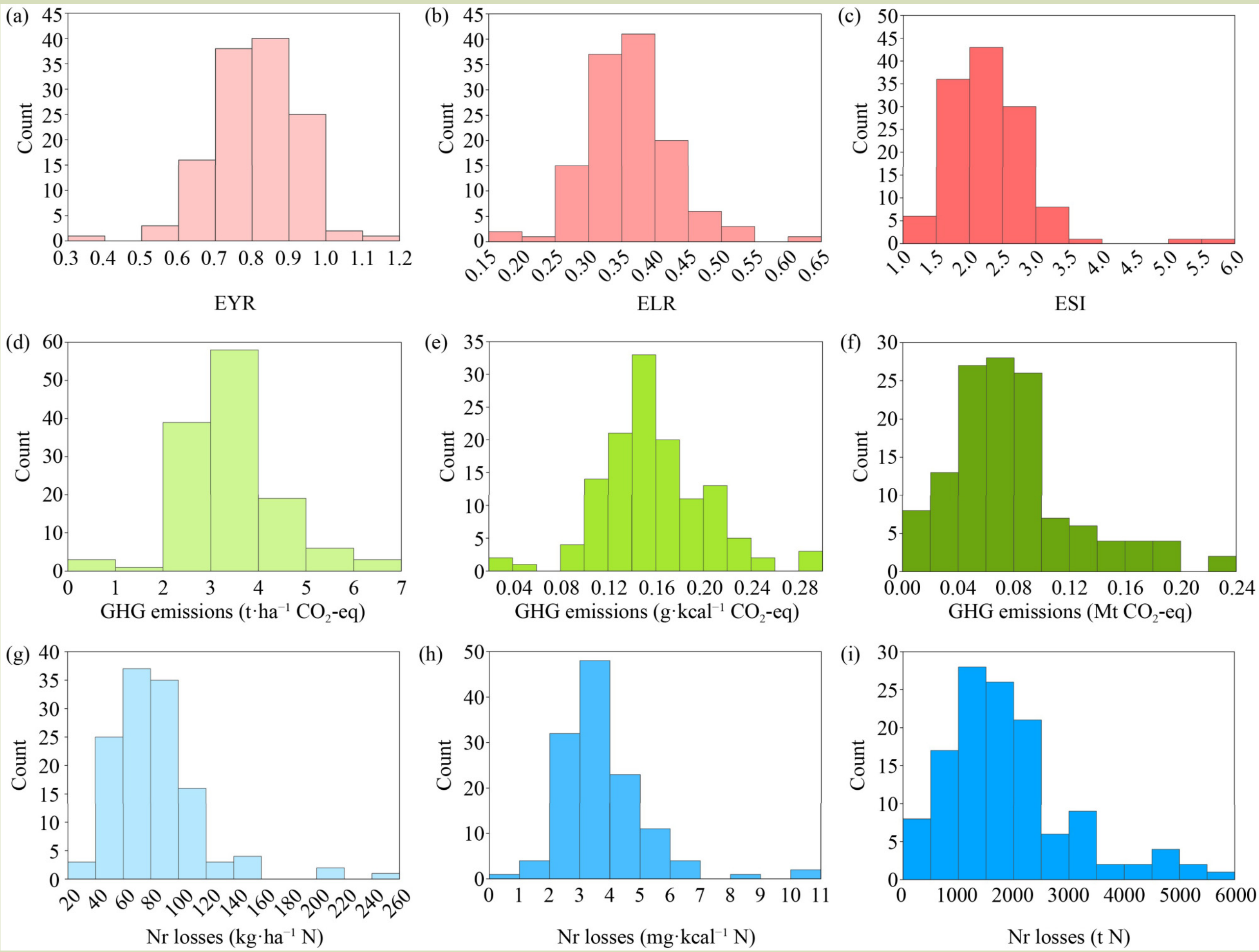

Fig. 2 Distribution of emergy yield ratio (EYR) (a), environmental loading ratio (ELR) (b), emergy sustainability index (ESI) (c), GHG emissions (d–f) and Nr losses (g–i) for maize in Hebei Province. GHG emissions are expressed in ton CO_2-eq per hectare harvested area (d), gram CO_2-eq per kilocalorie (e), total GHG emissions per county (f), Nr losses are expressed in kilogram N per hectare harvested area (g), milligram N per kilocalorie (h), and total Nr losses per county (i).

Province emitted less GHGs (Fig. 2(e)).

The total GHG emissions from maize production in each county varied from 660 t to 0.23 Mt, with an average of 0.08 Mt. Cang County emitted the most GHGs, followed by Yutian County, Linzhang County, Fengrun District and Shenzhou City, which is mainly attributed to the relatively high maize production of these cities (accounting for 7% of the total maize production in Hebei). In the west of Hebei, the total GHG emissions were relatively low (Fig. 2(f)).

3.1.3 Nitrogen footprint

The distribution of Nr losses for maize is shown in Fig. 2. The Nr losses per unit area of maize production in 126 counties ranged from 21.1 to 246 kg·ha^{-1} N, with an average of 83.4 kg·ha^{-1} N (Fig. 2(g)). The Nr losses per kcal maize ranged from 0.92 to 10.6 mg·kcal^{-1} N, with an average of 3.75 mg·kcal^{-1} N (Fig. 2(h)). The hotspots of Nr losses both per unit area and per calorie were mainly concentrated in Guangping, Wangdu and Qian'an city, which is attributed to the high nitrogen fertilizer inputs.

The total Nr losses from maize production in each county had obvious spatial heterogeneity, ranging from 18.5 to 5720 t N, with an average of 1890 t N. The counties with high Nr losses were concentrated in Cang, Linzhang, Qian'an, Fengrun and Shenzhou, due to the high application rates of nitrogen fertilizer. Also, the counties with low Nr losses were concentrated in the west of Hebei Province (Fig. 2(i)).

3.1.4 Cost-benefit analysis

The cost of maize production ranged from 11,200 to 14,200 CNY·ha^{-1}, with an average of 12,700 CNY·ha^{-1}, of which the human labor cost contributed the most. In the east of Hebei, the cost per unit area was higher than the rest of the area (Fig. 3(a)). The net income of maize production ranged from ~5870 to 9400 CNY·ha^{-1}, with an average of 4340 CNY·ha^{-1} (Fig. 3(b)). The areas with higher net income per unit area were scattered, for example Kangbao County, Huai'an County, Funing County, and Fengnan District. In some counties, the cost per unit area was not proportional to the net income, for example Kangbao County where the cost per unit area was lower but the net income was relatively high with a high yield. Due to the low nitrogen and phosphate fertilizer input costs, and yield, both the cost and net income per unit area in Guyuan County were the lowest.

3.2 Improvement potential

Compared to the baseline S0 (business as usual case), S1, S2 and S3 increased the average ESI by 16%, 28% and 26% (Fig. 4(a)), reduced the mean GHG emissions by 13%, 30%, and 28% (Fig. 4(b)), and mean Nr losses by 11%, 32%, and 30% (Fig. 4(c)), respectively; the average net income increased by 83%, 32%, and 66%, respectively (Fig. 4(d)); Overall, S2 gave the greatest improvement potential for ESI, GHG emissions and Nr losses, followed by S3 and S1. However, for net income, S1 gave the greatest improvement potential, followed by S3 and S2.

For each county, the improvement in ESI, carbon footprint, nitrogen footprint and net income varied with optimization strategies. Overall, S2 was the best strategy with the largest improvement potential for 62% of counties in ESI, for 73% of counties in reducing GHG emissions and for 75% of counties in reducing Nr losses. However, S1 gave the highest improvement potential for 89% of counties in net income. In addition, S3 was more effective for 27% of counties in ESI and

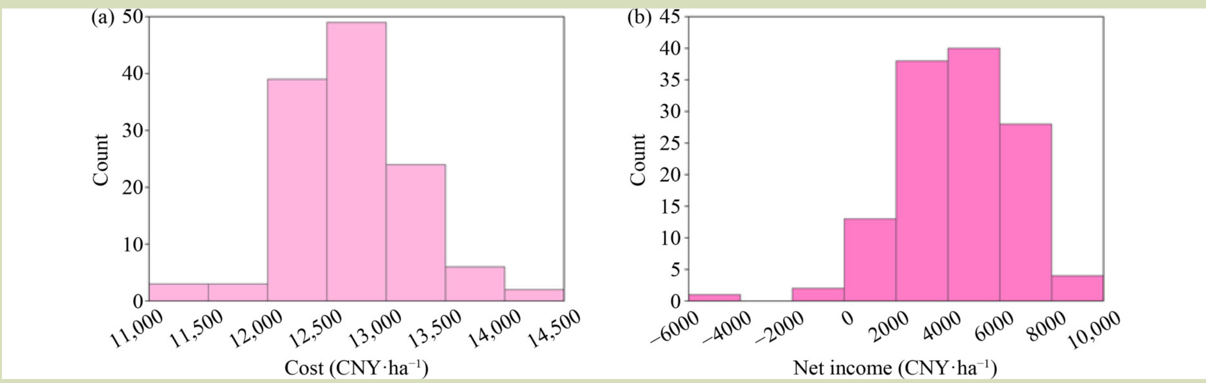

Fig. 3 The state of production cost (a) and net income (b) for maize in Hebei Province.

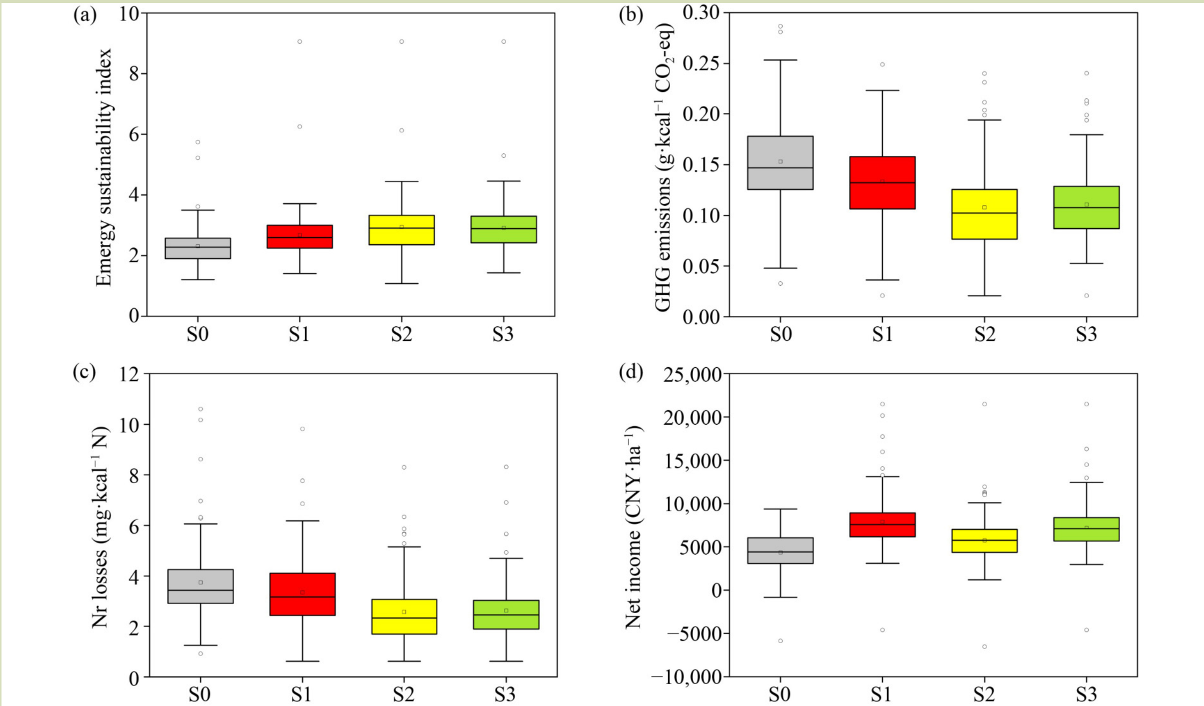

Fig. 4 The emergy sustainability index (a), GHG emissions (b), Nr losses (c) and net income (d) of maize production with different scenarios.

5% of counties in net income, and 24% of the counties in reducing GHG emissions and Nr losses. To enhance ESI of maize production, about 10% of the counties were more suitable for S1, while less than 3% of the counties reduced GHG emissions and Nr losses under S1. Therefore, with optimized strategies adopted, the average ESI and net income could increase by 32% and 83%, respectively, the average GHG emissions and Nr losses would decrease by 33% and 35%, respectively (Fig. 5). These optimization potentials were higher than adopting same strategies.

3.3 Uncertainty analysis

Uncertainty of carbon footprint and nitrogen footprint analysis comes mainly from the downscaled data associated with pesticides, plastic mulch, electricity, fuels and seeds, and emission factors. We assumed these activity levels and emission factors obey the normal distribution[32–34] and the coefficient of variation is 10%[35]. Monte Carlo simulation is selected to estimate uncertainties with 10,000 random sample generation, and results show the uncertainties of GHG emissions and Nr losses estimates of maize in 126 counties of Hebei at the 95% confidence interval are (~66%–85%) and (~61%–69%), respectively.

4 DISCUSSION

The average ESI of the maize production system in Hebei Province for the period studied was relatively low (2.3), indicating that there was a great potential to improve the sustainability of the system. The overuse of nitrogen fertilizer generated a large amount of GHG emissions and Nr losses, and decreased the sustainability of production systems in some counties, for example Guangping County and Qian'an City. In contrast, some of the counties (e.g., Kangbo and Gaoyi County) had large ESI but low GHG emissions and Nr losses, due to the relatively high nitrogen use efficiency. Some counties, for example Gaoyang, Julu, and Xinhe, emitted more GHGs and Nrs while being more sustainable in maize production. This is mainly attributed to the high input of irrigation water and manure as a renewable purchased resource. The average cost of maize production in Hebei Province was 12,700 CNY·ha^{-1} and human labor cost contributed most, indicating that agricultural production in Hebei was heavily dependent on the workforce. With optimal strategies adopted, the average ESI and net income could increase by 32% and 83%, respectively, and the average GHG emissions and Nr losses would reduce by 33% and 35%, respectively, suggesting the need for localized strategies. The economic benefits under S1 would be superior, but S1 would be not the best option considering its

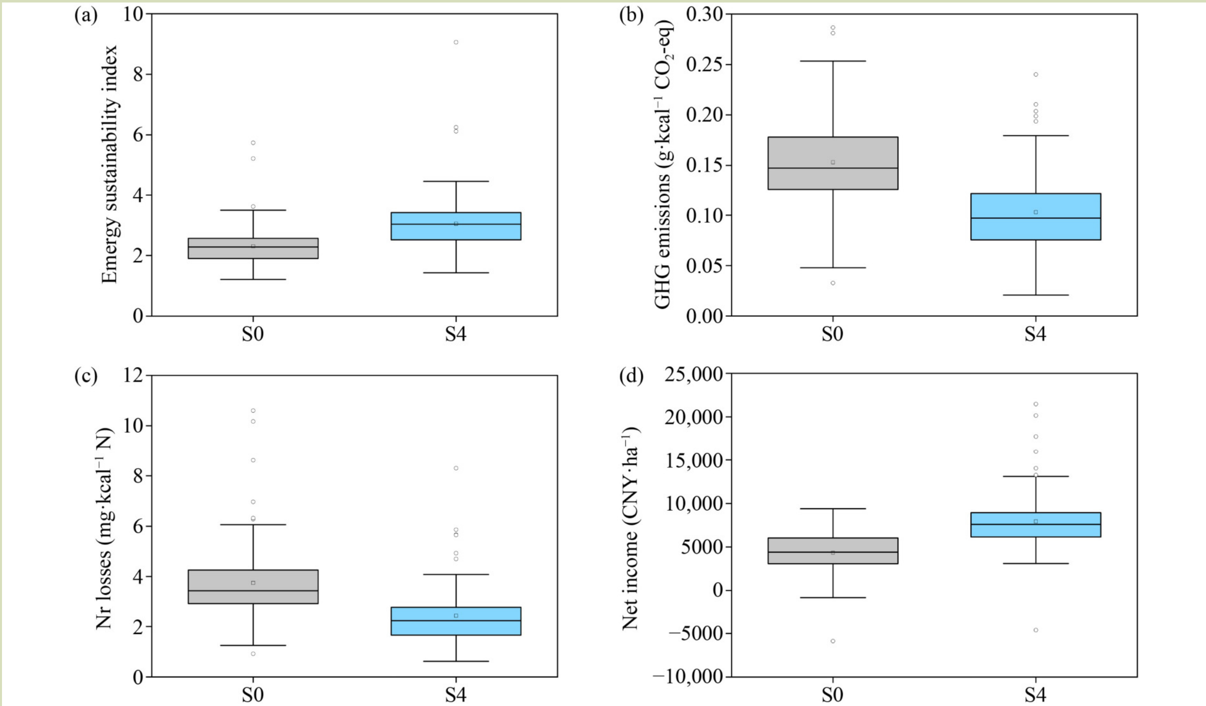

Fig. 5 Optimal strategies for improving the emergy sustainability index (a), GHG emissions (b), Nr losses (c) and net income (d) of maize production in Hebei Province.

environmental performance.

In the difficult quest for achieving sustainable agriculture for smallholders production systems, we recommend facilitating China's agricultural transition from three aspects: overall layout, technical innovations and field demonstrations. First, policy frameworks should be developed to cover the concerns about modernizing the basic rural operation system, socialized services systems for agriculture, talent cultivation and technical innovations[36]. Second, technically, a green transition for agriculture can progress through three phases: optimize, replace and redesign[37]. The initial step is the optimization of resource use efficiency, especially nitrogen fertilizer, mainly through adopting technologies like 4R technology[38], digital agriculture[39], soil testing and fertilizer recommendation[40,41], knowledge-based nitrogen management[42], and straw return[34,43]. The replacement phase relies on substitute technologies, including new phenotyping technology (e.g., increasing yield potential and resource use efficiency)[44,45], upstream mitigation from the supply chain of agriculture input (e.g., electrical synthesis of ammonia[46]) and alternative of electricity. The redesign phase entails a complete system redesign of agricultural practices, for example, integrated soil-crop system management[47] and precision agriculture[48], which still requires multiple cycles of development. Third, the collaborative weaving of research and practice restructured the relationship between farmers and researchers via on-farm experimentation[48], the Science and Technology Backyard[49] platform, and other co-production modes[50]. Farmers have knowledge of the background and circumstance that will underpin localization production, while researchers have responsibility for technical innovations and integrating capabilities. Combined with the local resource endowments and policymaking, they can harness community of interest, ensuring the implementation and promotion of technical innovations.

5 CONCLUSIONS

China's smallholders production systems face enormous challenges to achieve environment-economy sustainability. In this study, we took maize production in Hebei Province as an example and provided a spatially explicit assessments of the smallholders production system from multiple sources. Results indicate a great potential to improve the environmental-economic sustainability of the maize production system on smallholdings. And the environmental and economic indicators exhibit spatial heterogeneity among counties, indicating the necessity of localized optimization strategies for improving the environment-economy sustainability. The transition pathway of smallholders production systems requires comprehensive policy making, technical innovations, and associated promoting. Meanwhile, our study provides an important reference for countries facing the challenge of smallholders production system transition for the future. Although the downscaled data (e.g., pesticide, seed, plastic mulch and fuel) add some uncertainty to the process, our results should to a greater or less degree reflect county situations based on the large-scale surveys of farmers. Future studies should focus on obtaining more precise data via nationwide investigations and digital technology.

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Compliance with ethics guidelines

Jie Yan, Yize Liu, Rui Zhang, Chenhui Cui, Yingying Zheng, and Minghao Zhuang declare that they have no conflicts of interest or financial conflicts to disclose. All applicable institutional and national guidelines for the care and use of animals were followed.

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