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RESEARCH ARTICLE

A WAY TO SUSTAINABLE CROP PRODUCTION THROUGH SCIENTIST–FARMER ENGAGEMENT

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KEYWORDS

food security, scientists and farmers innovate together, greenhouse gas emissions, emergy ecological footprint, environment footprint

HIGHLIGHTS

- Farmer–scientist collaboration for improved farming was achieved.
- Wheat and maize yields of STB farmers improved by 13%.
- NUE increased 20% for wheat and maize production.
- GHG emissions and EEF decreased by 23% and 52%, respectively.

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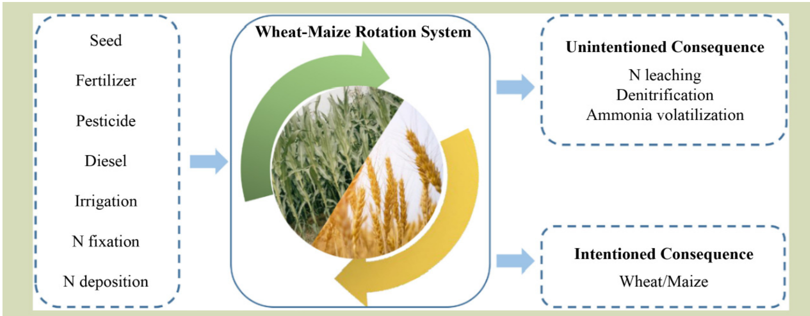
GRAPHICAL ABSTRACT



ABSTRACT

Feeding a large and growing population with scientifically sustainable food production is a major challenge globally, especially in smallholder-based agricultural production. Scientists have conducted a considerable theoretical research and technological innovation to synergistically achieve increased food production and reduced environmental impact. However, the potential and feasibility of synergistic smallholder-led agricultural production to achieve increased food production and environmental friendliness is not yet clear. Exploring the potential and feasibility of smallholders to synergistically achieve these two goals, this research collected survey data from 162 farmers implementing standard farming practices and 112 farmers engaged in Science and Technology Backyard (STB) in Quzhou County, Hebei Province, China. Grain yield, nitrogen use efficiency (NUE), greenhouse gas emissions (GHG), and emergy ecological footprint (EEF) of the wheat-maize cropping system dominated by smallholders were analyzed. The results showed smallholders in the STB group improved wheat and maize yields by about 13% and NUE by 20%, respectively. Also, a reduction of 23% in GHG emissions and 52% in EEF were simultaneously achieved in the wheat-maize cropping system. Compared with standard farming practices, 75 kg·ha^{-1} nitrogen-based fertilizer was saved in the STB farmers. In summary, this study shifts the main perspective of research from scientists to smallholder, and uses a combination of greenhouse gas emission calculations, EEF and material flow analyses to demonstrate from multiple perspectives that agricultural systems under the leadership of smallholders can synergistically achieve high crop yields and low resource use and environmental impacts. The results of this study also show that the smallholder-led scientist-farmer collaborative model established by STB can fully exploit the initiative and potential, and that this collaborative model can be a successful strategy for smallholders as operators to achieve food security at low environmental impacts. The results of this study can provide useful evidence for a sustainable shift toward more sustainable agricultural production systems.

1 INTRODUCTION

Achieving a sustainable supply of food for a growing population with appropriate external resource inputs is one of the great challenges in the context of current global agricultural development[1]. China has successfully produced approximately 22% of global food with only 9% of the global area cultivated during the last half-century[2], which is created with the world's 30% mineral fertilizers[3], also resulted in aquatic eutrophication and high N deposition[4]. Traditionally, the main goal of the agricultural system is to produce more food to meet the human demand, especially in developing countries[5]. Meanwhile with the development of the economy and improvement of living standards, the requirement of human for agricultural systems have become more diversified[6]. Maintaining high resource use efficiency, low environmental burdens and emergy footprints while ensuring a sufficient supply of food has been the key trends in the new era route to sustainable transformation in agriculture[7].

Quantifying and assessing multiple factors together is required to assist in decision-making regarding sustainable agricultural systems[8]. In this research, smallholders were considered as the main subject of the study, while three perspectives of greenhouse gas emissions, emergy ecological footprint (EEF) and material flow analysis were analyzed in an integrated manner. In contrast, many studies on agricultural production so far have been dominated by scientists, with smallholders as the real adopters of agricultural production and technology only as participants, and most studies have focused on a single objective without achieving multiple objectives[9,10]. For example, Ju and Christie showed that to achieve a target yield of 8.5 $t \cdot ha^{-1}$ on the North China Plain, the theoretical N application for maize season production should be 177–190 $kg \cdot ha^{-1}$[11]. Studies have shown that straw returned to the field can increase yields by 6.99% when combined with the use of 300 $kg \cdot ha^{-1} \cdot yr^{-1}$, while without fertilizer there is a 2.42% yield reduction[12]. Pu found that no-till in the winter wheat season reduced N_2O by 22.6% compared to standard tillage[13]. Springmann's research showed that the environmental impact of food systems can be reduced by 3%–30% through agrotechnical changes[14]. It remains unclear whether increasing crop production would lead to compromises in resource use efficiency, emergy footprint, and environmental outcomes. It is worth noting that we can also see from some of the recent studies that the goals of technology are gradually changing from single goals to multiple goals, and these findings also demonstrated the potential for multiple goals to be achieved synergistically, like optimal N fertilizer management techniques can increase wheat yields by 56.1% on the North China Plain while increasing N fertilizer bias productivity by 24% and reducing GHG emissions by 13%[15,16]. A better understanding of this process is extremely important in identifying the potential for future sustainable agricultural development.

Multi-objective agricultural production is complex, requiring not only multi-objective-oriented technology, but also multi-subject participation. The situation in developing countries is more daunting, as smallholders contribute more than 50% of the production of crops, such as wheat and maize. Due to limited in-time information and resources, smallholders do not have sufficient opportunity to access the advanced technology. A recent meta-analysis also shows that smallholders have higher yields and better biodiversity, but lower productivity per unit and higher responsiveness to GHG emissions as their scale increases[17]. Smallholders face many risks in agricultural production and lack access to knowledge, technology and the ability to cope with risk. In addition, previous studies, conducted in China, have shown that smallholders are adaptable, and through training or demonstrations, their output could be increased by 9.8%[18]. However, it is not clear how best to enhance the ability of smallholders to achieve high yields, while maximizing resource use efficiency and minimizing negative environmental impacts in the agricultural system dominated.

Therefore, we chose Quzhou, a typical agriculture production county dominated by smallholders on the North China Plain, as our survey area, and completed tracking analyses and farmer intervention of common farmers and STB farmers, respectively. The objectives were (1) to identify the current production status and major constraints of smallholder-dominated wheat-maize cropping systems, and (2) to explore potential ways to achieve multiple objectives crop production dominated by smallholders.

2 MATERIALS AND METHODS

2.1 System boundaries

The study area was in Quzhou, Hebei Province (114°50′22″ E to 115 °13′27″ E, 36°35′43″ N to 36°57′00″ N), a typical agricultural area on the North China Plain. The cultivated land area covers 50 kha and accounts for 75% of the total land area, with over 93,000 farming families living in 342 villages within 10 towns. Winter wheat-summer maize is the predominant cropping system. The region has a warm, subhumid continental monsoon climate, with an average annual temperature of 13 °C and precipitation of 556 mm. It is the main food-producing area of China because of its favorable climate and fertile soils, consequently, agriculture is of major importance to this county.

In the study, we used a nutrient-derived environmental impact assessment (NEIA) model to quantify the environmental impacts of agricultural production[19]. The model is established by combining the life cycle assessment method with the mass balance principle of substance flow analysis. A schematic representation of the NEIA model is shown in Fig. 1. This study analyzes four environmental impacts, including energy consumption and GHG emissions, which are mainly caused by nutrient inputs and losses in wheat and maize production. For the purposes of this study, the appropriate functional unit for this system is per hectare.

2.2 Data sources

The survey was conducted over a 1 km × 1 km grid in Quzhou County in March 2018. Data was collected from two categories of farmers: farmers using the currently most common (standard) farming practices (FP farmers;), and farmers engaged in STB programs (STB farmers; n = 112). The data for FP farmers were collected through a county-wide survey, while the data for STB farmers were obtained through long-term follow-up interviews with farmers participating in the STB project. The indicators collected for the two categories of farmers included wheat and maize cultivars,seeding rate and date, yield, amount of mineral fertilizer use (N, P, K), as described in Table S1 and Table 1.

The STB farmers were eager to participate in technological innovation and knowledge transfer through the STB platform established in a typical wheat-maize rotation village, Wangzhuang. Smallholders work with STBs and conduct field trials together in their fields. Smallholders take the initiative in exploring approaches and mechanisms for technology localization with the assistance of STB scientists and graduate students.

2.3 N flow in wheat-maize production by substance flow analysis

Substance flow analysis was used to quantify the flow of N from the time of sowing to harvest with mass balance calculations and the first law of thermodynamics in the whole system, which was divided into three parts based on the form and role of nitrogen, including nitrogen input (N_{in}; kg·ha^{-1}), nitrogen output (N_{out}; kg·ha^{-1}) and nitrogen accumulation. First, nitrogen presented in the input part: fertilizer ($N_{fertilizer}$;

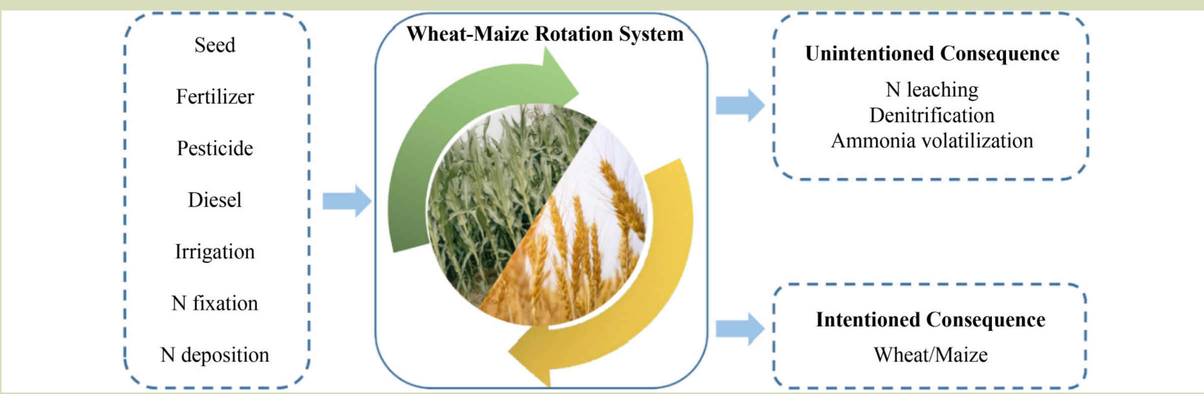


Fig. 1 Logical framework of the model of the nutrient-derived environment in wheat-maize production.

Table 1 Comparison of grain yield, mineral N fertilizer, and N use efficiency of wheat-maize cropping system with standard farming practices (FP) and STB farming (STB) in Quzhou County, Hebei Province, China

Crop	Treatment	Yield ($t \cdot ha^{-1}$)	Mineral N fertilizer ($kg \cdot ha^{-1}$ N)	N use efficiency* (%)
Maize	FP (n = 162)	9 ± 1.3b	248 ± 81a	69 ± 21b
	STB (n = 112)	9 ± 1.1a	194 ± 61b	93 ± 27a
Wheat	FP (n = 162)	8 ± 0.8a	264 ± 81a	68 ± 18b
	STB (n = 112)	9 ± 0.4b	243 ± 33b	89 ± 18a

Note: *, N use efficiency indicates ratio of nitrogen aboveground removal to N fertilizer input; a, b indicate there was a significant difference ($P \leqslant 0.05$); n indicates the number of samples.

$kg \cdot ha^{-1}$), seed (N_{seed}; $kg \cdot ha^{-1}$), irrigation ($N_{irrigation}$; $kg \cdot ha^{-1}$), nitrogen deposition ($N_{depositon}$; $kg \cdot ha^{-1}$) and biological nitrogen fixation ($N_{bio\text{-}fix}$; $kg \cdot ha^{-1}$). Secondly, nitrogen output including grain obtained from crop harvest, denitrification of fertilizer and nutrient leaching loss ($N_{leaching}$; $kg \cdot ha^{-1}$). Lastly, N accumulation, considering its total inflow and total outflow the quantity of N stored via N accumulation in soil ($N_{accumulation}$; $kg \cdot ha^{-1}$).

$$N_{input} = N_{fertilizer} + N_{irrigation} + N_{deposition} + N_{seed} + N_{biological} \quad (1)$$

$$N_{output} = N_{uptake} + N_{loss} \quad (2)$$

$$N_{loss} = N_{leaching} + N_{runoff} + N_2O_{emission} \quad (3)$$

$$N_{accumulation} = N_{input} - N_{output} \quad (4)$$

All the coefficients of the calculations (N_{input}, N_{output} and N_{loss}) are listed in Table S2.

2.4 N use efficiency

N use efficiency (NUE) was calculated as the ratio of total N uptake by crop harvest and the total N input in the wheat-maize production system:

$$NUE = \frac{N_{uptake}}{N_{input}} \quad (5)$$

$$N_{uptake-maize} = 23.3 \times Y_{maize}^{0.887} \quad (6)$$

$$N_{uptake-wheat} = -14 + 41 \times Y_{wheat}^{0.77} \quad (7)$$

where, $N_{uptake-wheat}$ is crop N uptake in wheat and $N_{uptake-maize}$ is crop N uptake in maize. Y_{maize} is maize yield, Y_{wheat} is wheat yield. More detailed calculation steps and methods are detailed in a previous study[15,16].

2.5 GHG emission in wheat-maize production by life cycle assessment

The GHG emissions calculated in this study for wheat-maize production under the dominance of two farmer types in Quzhou County were quantified using a life cycle assessment approach, which can reflect the current status of agricultural production in the study area while fully incorporating regional characteristics. Defined as the entire production process: energy consumed by agriculture and other inputs used for production externalities, corresponding agronomic practices, and agricultural machinery. Combining the pathways of GHG production with direct or indirect emission methods, we divided GHG into the following units in the calculation session. We defined the total GHG emissions for the whole life cycle as GHG_{total} ($kg \cdot ha^{-1}$ CO_2-eq), including carbon dioxide, nitrous oxide and methane, expressed in carbon equivalents (CO_2-eq). GHG emissions were associated with the application, production and transport of nitrogen fertilizers, production and transport of phosphorus and potassium fertilizers, as well as herbicides and pesticides and diesel fuel used for seeding, harvesting and tillage.

For total N_2O emissions during wheat and maize cultivation, including direct and indirect N_2O emissions, which could not be measured directly in this study, calculations were made based on previous studies[16] using the IPCC methodology for calculating indirect N_2O emissions, which showed that 1% and 0.75% of the volatilized N-NH_3 and leached N-NO_3 were lost as N_2O-N. The GHG emissions from the total N_2O emissions were calculated in units of CO_2 equivalents (CO_2-eq) over a 100-year time period and were 298 times the intensity of CO_2 on a mass basis.

$$GHG_{total} = (GHG_m + GHG_t) \times N_{fertilizer} + N_{N_2O} \times 44/28 \times 298 + GHG_{others} \quad (8)$$

where, GHG_m (kg CO_2-eq kg^{-1} N) and GHG_t (kg CO_2-eq kg^{-1} N) are the GHG emissions from fossil fuel used for mineral N manufacturing and transportation per unit of mineral N fertilizer; $N_{fertilizer}$ ($kg \cdot ha^{-1}$ N) is the N fertilizer application rate; GHG_{others} represents GHG emissions associated with the production and transportation of P and K fertilizer, production and transportation of pesticides, and consumption of diesel fuel.

2.6 Emergy ecological footprint in wheat-maize production by life cycle assessment

Scientific qualitative, quantitative and integrative analysis of the sustainability of specific ecosystems has been a popular topic of research. The three main methods used in many previous similar studies are emergy analysis, ecological footprint (EF) and EEF, all three are simply and widely used methods, but the first two have their own limitations. uniqueness, ignoring the differences in material and energy flows between different regions and the role of energy sources other than solar energy in driving ecosystems[20], while EEF only focuses on the material cycles in ecosystems and the sustainability of ecosystems in a static framework, ignoring the influence of other factors and not reflecting the trends of ecosystems in a given period.

The EEF model, which combines the advantages of the above two research methods and has objective, quantifiable characteristics, was used to conduct a scientific and systematic objective analysis and comparison of the sustainability of two different types of farmer-led wheat-corn cropping systems in Quzhou County.

The EEF was calculated using the following equation:

$$\text{Emergy} = \text{mass (or energy)} \times \text{transformity} \tag{9}$$

$$\text{EEF} = \frac{\text{ST} + \sum \text{I}_i}{\text{GED}}, \tag{10}$$

where, emergy is energy value (J); mass is substances (g); transformity is solar transformity (sej·g^{-1} or sej·J^{-1}). EEF is the emergy ecological footprint (ha); ST is electrical energy used for water pollution treatment (sej); I_i is energy value of various agricultural inputs for grain production (sej), and GED is the global energy density taking the value of 3.1 × 10^{10} sej·m^{-2}·yr^{-1}, derived from the results of Zhao et al.[21].

2.7 Emergy ecological carrying capacity

The emergy ecological carrying capacity (ECC) reflects the supply capacity of natural resources in the study area. Natural resources are divided into renewable and non-renewable resources. In this study, the following renewable natural resources were selected: solar energy, rainwater potential energy, rainwater chemical energy and earth rotation energy.

The ECC is calculated using the following equation:

$$\text{ECC} = \sum \frac{\text{Re}_i}{\text{GED}}, \tag{11}$$

where, ECC is the emergy carrying capacity (ha), Re_i is renewable natural resource emergy.

2.8 Emergy output capacity

The emergy output capacity (EOC) reflects the level of output of the study object and is a measure of productivity. Estimation of emergy per unit area output capacity.

$$\text{EOC} = \frac{\sum \text{G}_i}{\text{GED}} = \frac{\text{W} + \text{M}}{\text{GED}} \tag{12}$$

where， G_i is the emergy contained in the crop output (sej); W and M correspond to the emergy contained in the yield of winter wheat and summer maize (sej), respectively.

To measure the sustainability of maize-wheat production, the following three indicators were used: resource load index (RLI), environmental load index (ELI) and sustainability index (SI).

$$\text{RLI} = \frac{\text{EEF}}{\text{ECC}} \tag{13}$$

$$\text{ELI} = \frac{\text{EnF}}{\text{EOC}} \tag{14}$$

$$\text{SI} = \frac{\text{EOC}}{\text{EEF}} \tag{15}$$

where, EnF is the environmental footprint, it is the energy consumption due to water pollution management.

2.9 Data analysis

The software packages for data analysis and representation included Origin 2019, SPSS Statistics 26 and Microsoft Excel. The N flows of wheat and maize production were plotted using e!Sankey pro (version 4.1, ifu Hamburg GmbH, Hamburg, Germany). Significant differences among means were determined by LSD at $P \leqslant 0.05$.

3 RESULTS

3.1 Changes of yield and mineral N fertilizer use based on FP and STB farming practices

High yields were achieved by STB farmers, with 9 t·ha^{-1} for both wheat and maize, respectively (Table 1). STB farmers achieved a wheat yield increase of 21% and maize yield increase of 7%. Compared with FP farmers, the N use efficiency of STB farmers improved significantly, due to a change in farming practices by the STB farmers because of their participation in research and training. FP farmers used 264 kg·ha^{-1} of mineral N fertilizer for wheat production and 248 kg·ha^{-1} for maize production, whereas for STB farmers the amounts were 243 kg·ha^{-1} for wheat production and 194 kg·ha^{-1} for maize production, indicating that 25% and 19% of STB farmers for wheat and maize production, respectively, reduced their mineral N fertilizer use. Wheat and maize yield for FP farmers was 17 t·ha^{-1}, a little lower than the yield of STB farmers which is 18 t·ha^{-1}.

3.2 N flow in the production of wheat-maize system

The N flow in wheat-maize cropping system for the FP and STB farmers is shown in Fig. 2. The total N input to the wheat-maize system for FP farmers (FP) was 575 kg·ha^{-1}, with approximately 89% of the amount originating from mineral N fertilizer. The harvested N value was 337 kg·ha^{-1}, accounting for 59% of the total N input in the wheat-maize production. As much as 40% of N was lost to the environment (NH_3 volatilization, N leaching and denitrification), and 6 kg·ha^{-1} accumulated in arable land. Compared with FP farmers, only about 11% of the total N input was reduced by STB farmers, but the N uptake in the wheat-maize system increased by 12%, and the N lost to the environment was reduced by 37%. More importantly, 24 kg·ha^{-1} N from the soil was assimilated by crops in the STB group.

3.3 GHG emission based on FP and STB farming practices

Clearly, the estimated GHG emissions of wheat-maize production varied with different farming practices (Fig. 3). The total GHG emissions of FP farmers were 8 Mg·ha^{-1} CO_2-eq, which was significantly higher than that of STB farmers (6 Mg·ha^{-1} CO_2-eq). For FP farmers, approximately 53% of the total GHG emissions were emitted from mineral N fertilizer use, and the total of N_2O emissions resulted in 31% GHG emissions, followed by GHG emissions from the consumption of diesel fuel, mineral P fertilizer use, mineral K fertilizer use, and the production and transportation of pesticides (Fig. S1). Compared with those of FP farmers, the practices of STB farmers reduced GHG emissions by 23% through reduced mineral fertilizer use, especially N consumption, and improved wheat and maize yields.

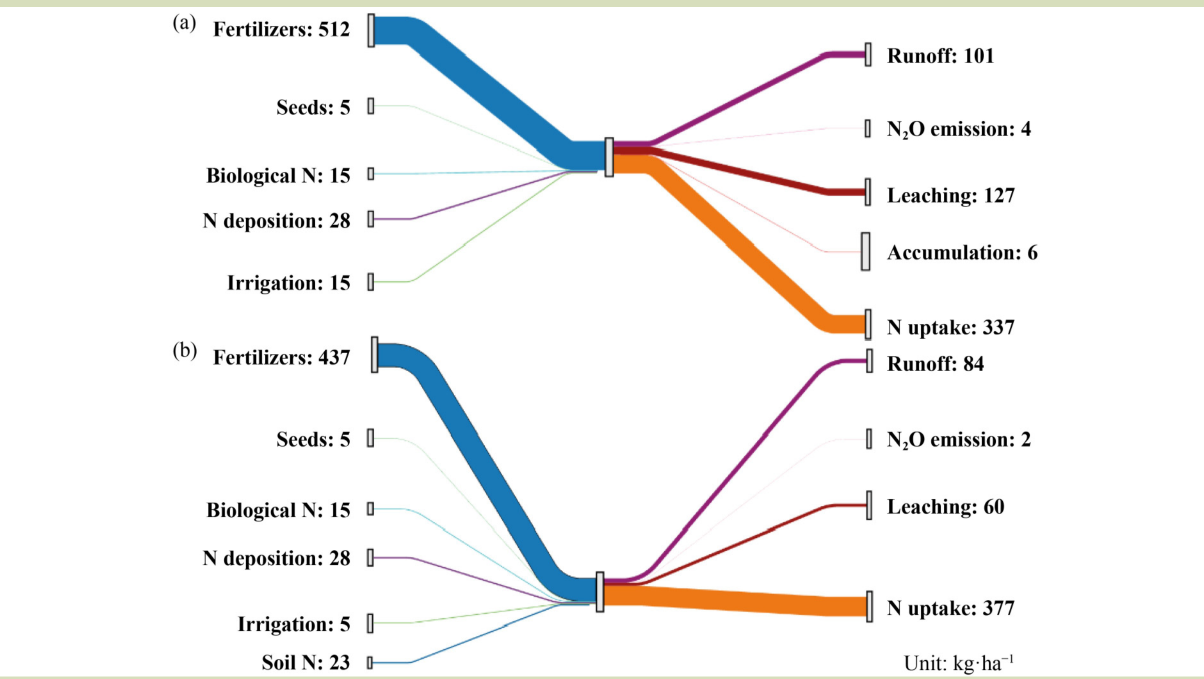


Fig. 2 Nitrogen flux (kg·ha^{-1} N) of wheat-maize production based on standard farming practices (FP) (a) and STB farmers (STB) (b) in Quzhou County, Hebei Province, China.

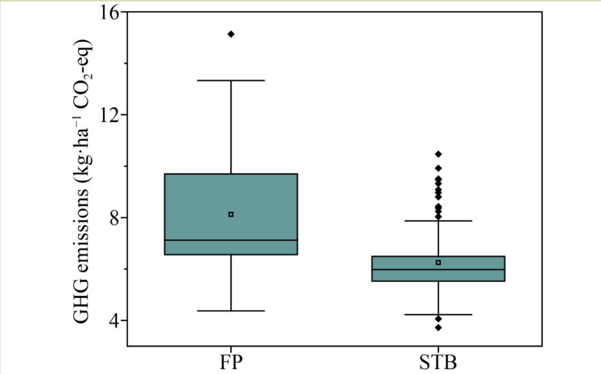


Fig. 3 GHG emissions (kg·ha^{-1} CO_2-eq) of wheat-maize production based on standard farming practices (FP) and STB farmers (STB) in Quzhou County, Hebei Province, China.

3.4 Evaluation of sustainability for wheat-maize production based on emergy ecological footprint

Compared to that of the FP farmers, the performance of the EEF of STB farmers decreased significantly (Fig. 4). The EEF was reduced from 70 ha for FP farmers to 33 ha for STB farmers, totaling decreased by 52%. An overview of the major contributors to the EEF of wheat-maize production based on FP and STB farming practices is presented in Fig. S2. The results show that the mineral N fertilizer use and electricity energy for water pollution treatment were the major contributors to EEF, regardless of FP farmers and STB farmers. The sustainability of wheat-maize production systems based on STB farmers could be improved. On average, the sustainability index from STB farmers was improved by 125%, while the resource load index and environment load index from STB farmers was reduced by 115% and 71%, respectively, compared with that of FP farmers (Fig. 5).

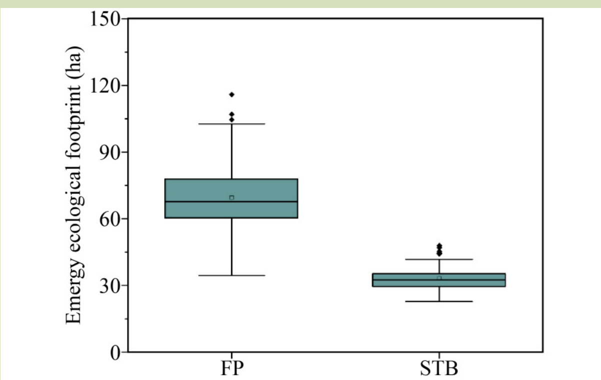


Fig. 4 Emergy ecological footprint (ha) of wheat-maize production based on standard farming practices (FP) and STB farmers (STB) in Quzhou County, Hebei Province, China.

4 DISCUSSION

Food systems across the planet face multiple challenges including increasing food supply, maximizing resource use efficiency and environmental impacts[14]. Notably, high yields are usually accompanied by high levels of resource input which inevitably leads to high environmental and emergy

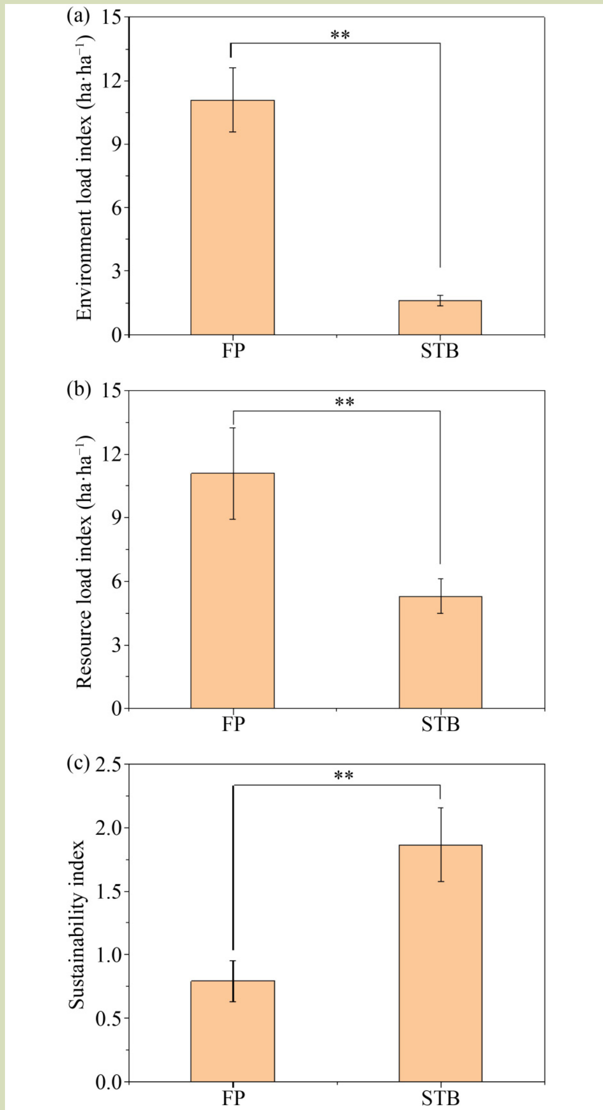


Fig. 5 Indexes of emergy ecological footprint of wheat-maize production based on standard farming practices (FP) and STB farmers (STB) in Quzhou County, Hebei Province, China: (a) environment load index, (b) resource load index, and (c) sustainability index.

footprints[18,22]. One of the key findings is wheat-maize yield of STB farmers improved by 21% and 7% respectively, compared with FP farmer yields. Simultaneously, the NUE increased by 21% and 24% for wheat and maize production (Table 1), while the wheat and maize total GHG emissions and EEF decreased by 23% and 52% (Fig. 3 and Fig. 4), which indicates that technological innovations realized by smallholders on their own land through training with STB and have great potential for achieving sustainability of agricultural systems. In the scientist-farmer approach, a small increase in wheat-maize yield was achieved with a corresponding decrease in environmental impacts. This shows that smallholders, who achieve technological innovation under the scientist-farmer approach model established by STB, have the potential to achieve multiple goals on their land, such as high yields and environmental reduction. Therefore, the collaboration of smallholders and scientists in learning technologies and improving agronomic management practices is a way to enhance farmer potential.

While striving for higher crop yields, low environmental impacts with mitigation of the associated environmental footprint (EnF), and resource use efficiency is a key factor limiting sustainable production in agroecosystems[23,24]. The NUE for maize and wheat production of STB farmers were 89% and 93%, which were 21% and 24% higher than FP farmers (Table 1). This shows great potential for improving the NUE in the intensive farmland system of the North China Plain. Low NUE values in North China are mainly due to smallholder mismanagement of wheat-maize production and lack of effective agronomy training, which has resulted in low levels of technological innovation[25,26]. NUE links the inputs and outputs of agricultural systems and is closely related to environmental losses[27]. Ensuring a sustainable food-secure future, China needs further technological innovation to attain higher yields and high NUE with a substantially reduced Enf.

Adapting technological innovation for local use could help improve yields, resources and environmental issues synergistically. According to the results of our study (Fig. 6(a,b)), 77% of STB farmers were in the yield range of 17 to 20 t·ha^{-1}, while for FP farmers only 32% were in this range. In addition, the overall mean fertilizer application of STB farmers was also 15%lower than that of FP farmers, besides with only 17% of STB farmers applying more than 500 kg·ha^{-1} fertilizers, but 44% of FP farmers. From the above analysis results can prove that through the scientist-farmer approach established by STB model, we make changes to the STB farmer, which fostered them to know what-how-when-where so that the group develops in a good direction including compared to FP farmers so that the STB farmers yield tips and fertilizer application is reduced, which is very different from the changes to the individual, only when the small farmers are really involved, the scientists can understand the farmer group comprehensively so that the changes can be effective.

Of particular note is the improved sustainability of STB farmer farming systems due to the development of appropriate, localized agricultural production technologies by scientists and smallholders together. Our results show that STB farmers have improved sustainability indices compared to FP farmers, while their resource load and environmental load indices have decreased, with GHG emissions decreasing by 23%, which is consistent with the results of Deng with a 16% reduction in GHG, respectively[25]. Compared to FP farmers, STB farmers improved their sustainability indices by adopting the results of experiments that demonstrated the merits of the proposed technical concepts. A comprehensive set of innovation management measures is the result of scientist-farmer engagement, which is not only a top-down approach where

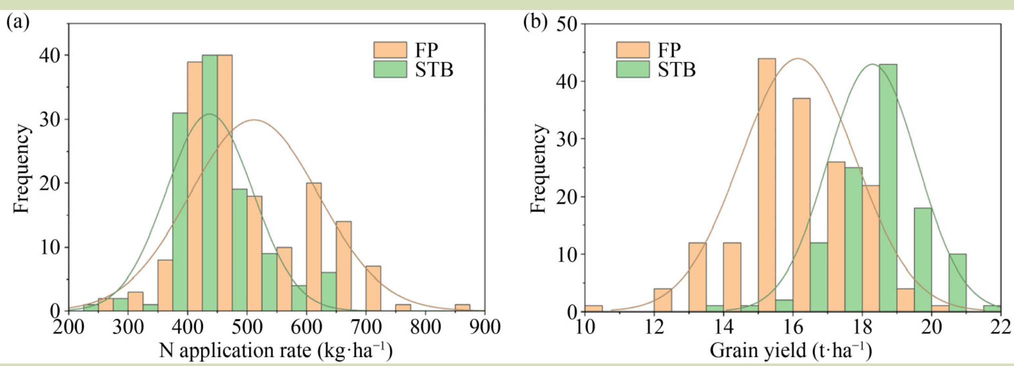


Fig. 6 Proportion (%) of N application rate for wheat and maize production (a), wheat and maize yield (b) for practices by STB farmers compared to standard farming practices (FP) in Quzhou County, Hebei Province, China.

scientists impose their findings and draw conclusions to answer the research questions, thus solving the research problems in isolation[18]. Our study provides an in-depth case for participatory research conducted as a collaboration of scientists and farmers.

If the actual solution to the production problem is still to be adopted by the common research model to find the problem and scientifically logical thinking[28], then the resulting output method is bound to be ineffective in solving the production problem, because it lacks the participation of the real production subject (i.e., smallholders), and does not deeply combine the needs and characteristics of smallholders, which is the loss of their participation and adoption of the initiative[18]. According to the study found that the participation of more stakeholders, so as to increase the relevance of feasible solutions[29]. The STB method offers a completely different perspective and approaches from previous research, we rely on collaboration of scientists and STB farmers, the impetus shifts to the farmer to discover and take the lead in exploring and solving production problems with the participation of scientists[16]. With the assistance of scientists, STB farmers conduct technological innovation experiments in their own fields and plant demonstration fields. At the same time, scientists use the STB platform to hold targeted training and competitions on planting technologies, such as high-yielding and high-efficiency competitions, in the process, not only to enhance STB farmer enthusiasm to participate but also to improve STB farmer knowledge and understanding to realize the empowerment of small farmers, and to realize the real technology on the ground. Farmers have mastered some planting techniques through STB platform, such as learning to select better cultivars, sowing at more suitable times and adopting more scientific management strategies, reducing the amount of nitrogen fertilizer applied by 14.7%, increasing yields by 13.3%, and reducing GHG emissions by 23.0%. This is also in agreement with the findings of Jiang[30].

Simultaneously, the role of scientists has changed from being purveyors of technological innovation to technological participants and instructors, who can encourage the inherent potential of farmers to assist with sustainable productivity. For example, scientists measure nutrient content of small and medium-sized farmer fields and give nutrient management advice directly to farmers, who adjust their nitrogen fertilizer applications through first-hand, reliable strategies that help achieve their desired crop yields at a lower cost of production[31]. In our research, smallholders are equipped with increased knowledge of sustainable maize-wheat production through scientist-farmer engagement and are capable of mastering the required technological skills. It also proves using the farmer knowledge, with the assistance of technologists, innovation is achieved through joint learning and knowledge cross-fertilization, a mutually beneficial process in which the relevant participants come together so that the farmer management decisions are supported[32].

In addition to localizing technological innovation through scientist-farmer collaboration, this strategy is more about enabling technology to be easily adopted by smallholders. The STB farmers understood the integrated nutrient management technology during scientist-farmer engagement and mastered the operation and use of the technology[33]. More importantly, STB farmers can effectively explain these new technologies to their neighbors to help increase its implementation in the region[34]. Using this approach, only a small number of new technologies are introduced to enable more smallholders to correctly adopt nutrient management technology.

The large-scale application of innovative localized technology through scientists and farmers participating together provides a good model for the transformation of agricultural production dominated by smallholders to ensure sustainable development in the future. For example, the analysis of stakeholders in the wheat supply chain found that STB farmers achieved both reduced emissions and increased economic returns compared to FP farmers, also demonstrating the potential of empowering smallholders through the STB method[25], which is essentially the same as the findings of this study this model provides an example for countries and regions facing the same problems such as India and Africa. However, agricultural production is a complex process, including soil science, plant science, nutrient management, economics and policy implementation[35].

Internationally, there are many models similar to the STB and these are unified as on farm experimental initiatives, which exist independently in their own unique contexts, but share the principles of farmer-centered expert support and collaborative learning, and have proven to be replicable and scalable[32].

5 CONCLUSIONS

The present study used questionnaire survey data from two categories of farmers (162 FP farmers and 112 STB farmers). It was found that compared with FP farmers, the STB farmers increased maize and wheat production by 21% and 7% as well as improved the NUE by 21% and 24%, reducing wheat and maize total GHG emissions by 23%. Using adaptive technology in maize-wheat production, Overall the production of wheat and maize greater than 16 t·ha^{-1} account for 97% of all STB farmers, while only 55.6% of FP farmers reached. As for N fertilizer rate, 44% of FP farmers used more than 500 kg·ha^{-1}, but only 17% of STB farmers.

A comprehensive analysis of the results combining GHG emissions, energy-ecological footprint and material flows shows that through scientist-farmer collaboration used by the STB, smallholders can fully apply their own initiative and potential to collaborate to achieve high food production, high resource efficiency, low GHG emissions and low emergy-ecological footprint. The goal is to achieve high food production, high resource efficiency, low greenhouse gas emissions and low emergy ecological footprint. Unlike other previous studies, smallholders have a leading role in this study, while scientists acted as facilitators and catalysts. At the same time, our findings confirm that STB is a proven method that combines top-down modeling and bottom-up participatory approaches to empower smallholders by focusing on their needs. It provides a more informative example for advancing the transition to sustainable smallholder-led agricultural production systems today and promoting the synergistic achievement of multiple goals.

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Compliance with ethics guidelines

Yu Guo, Ran Li, Peng Ning, and Xiaoqiang Jiao 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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