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Research Paper

Integrating production, ecology and livelihood confers an efficiency-driven farming system based on the sustainable farmland framework

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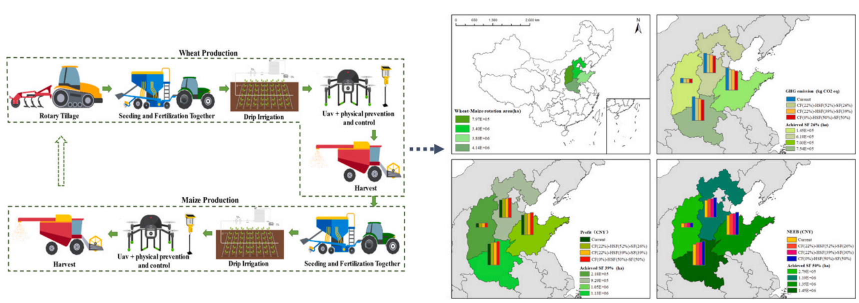
HIGHLIGHTS

- A new system boundary for farmland construction is identified.
- Environmental-economic benefits are evaluated on different farming systems.
- Sustainable Farmland - Intelligent farming mode (SF-ITFM) is measured to have the best comprehensive benefits.
- The potential of SF-ITFM in reducing emissions and increasing productivity is estimated.
- The improvement pathways on different farming systems are proposed.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Ensuring reduced carbon emissions and sustainable development in agricultural production are pivotal in addressing the multifaceted demands within farming systems, including safeguarding food security, advancing eco-friendly agricultural practices, and enhancing farmers' livelihoods. While an efficiency-driven farming system under the sustainable farmland has been recently introduced in China, integrating production, ecology, and livelihood aspects, its effectiveness remains unexplored in comparison to alternative farming systems. Moreover, the interplay among different elements within farming systems lacks comprehensive characterization.

OBJECTIVE: Typically, the three predominant farming systems comprise conventional farmland—smallholder farming mode, high-standard farmland—intensive farming mode, and sustainable farmland—efficiency-driven

Abbreviations: HSF, High-standard farmland; SF, Sustainable farmland; CF, Conventional farmland; CF-SFM, Conventional farmland—smallholder farming mode; HSF-IFM, High-standard farmland—intensive farming mode; SF-EDFM, Sustainable farmland—efficiency-driven farming mode; NABE, New Agricultural Business Entity; LCA, Life cycle assessment; LCC, Life cycle cost; CBA, Cost–benefit analysis; NEEB, Net Ecosystem Economic Benefit; CNY, Chinese Yuan.

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farming mode. In this study, the system boundary of farmland construction is identified, elucidating how various interrelated forms of farmland infrastructure development and cropping management practices affect the environmental and economic efficiency.

METHODS: The integrated benefits of the farming systems were evaluated by investigating life cycle characteristics, life cycle cost, cost-benefit analysis and Net Ecosystem Economic Benefit (NEEB) under wheat—maize cropping. Furthermore, simulation was conducted to explore the development potential of the farming system with the greatest integration benefits and regional contribution magnitude.

RESULTS AND CONCLUSIONS: The results demonstrate that sustainable farmland—intelligent farming mode not only reduces resource inputs but also enhances productivity. Moreover, it positively contributes to regulating nitrogen losses, nitrogen and carbon footprint and greenhouse gas (GHG) emission. Furthermore, this mode represents an optimal economic approach, leading to a total decrease in CO_2 emissions of 9.01E+07 t, an increase in net ecosystem economic benefits of 101 billion Chinese Yuan, and a rise in grain yields of 1278 t in the North Plain of China.

SIGNIFICANCE: This study emphasizes the significance of enhancing precise cropping management practices and advanced farmland infrastructure to promote development of efficiency-driven farming systems. Furthermore, strategies for improving various farming system should be tailored to their unique characteristics and adaptability.

1. Introduction

To advance the United Nations Sustainable Development Goals (SDGs), proactive measures are being implemented to improve the global agricultural system. The total grain production has consistently exceeded 650 million tons for 8 consecutive years in China, with a 0.5% increase in 2022[2], making a significant contribution to achieving “Zero Hunger” of the SDGs. However, it is assessed that adverse ecological environment continues to pose challenges to achieving the 2030 strategic target in China.[3] In particular, the extensive management practices reliant on resource consumption bring about negative environmental impacts, the decreased marginal effect of increased grain yields in agriculture production (Han and Zhang, 2020; Jingjing et al., 2019; Liu et al., 2018; Wanger et al., 2020) .

In recent years, Chinese government has implemented a series of green development initiatives aimed at promoting sustainable agricultural transformation, establishing an environment conducive to efficient output, resource conservation, and eco-friendliness. Transforming the traditional cropping management mode has been a key focus, achieved through technological innovation, mechanization promotion, and appropriate scaled farming (Gou et al., 2015; Liao et al., 2022; Yang et al., 2021). Consequently, industrial agricultural organizations, often referred to as New Agricultural Business Entities (NABE), have been developed, comprising 3.9 million family farms and 2.2 million farmer cooperation units to date.[4] Simultaneously, the construction of high-standard farmland (HSF) has emerged as a priority strategy, integrating land consolidation, improving machine road, irrigation ditch, and other infrastructural enhancements. By 2020, a total of 53 million ha of HSF had been constructed (Yin et al., 2022).

With the promotion of constructing HSF, the Chinese government issued the “no.1 document”, stabilizing the area of grain production and focusing on crop yield in 2023, which requires that agriculture production should fulfill the commitment reducing carbon dioxide emissions and ensuring carbon neutrality to maintain low-carbon and high-quality development.[5] Therefore, integrating “production, ecology and livelihood” has become an important measure in constructing sustainable farmland (SF) to meet the aforementioned requirements.[6] In the SF proposal, a novel system boundary of farmland construction was proposed, primarily consisting of farmland infrastructure construction and cropping management activity. In detail, under the guidance of “guaranteeing food security, promoting eco-friendly farmland and increasing farmers’ income”, “new round of enhancement action aiming to increase grain production capacity by 50 million tons” should be coordinated by improving infrastructure facilities and transforming cropping management. However, 70% of cultivated land is still managed by smallholders, while the remainder is under the management of NABE,[7] resulting in a difference in cropping management and farmland infrastructure condition because of various operation modes among different agricultural producers. Therefore, determining how to align infrastructure conditions with cropping management practices become a key step in identifying farming system types. Moreover, conducting quantitative assessments on the multi-benefits in different farming systems also play a crucial role in establishing effective farming systems and provides valuable insights for maintaining sustainable agriculture development.

The current assessment on farmland construction effectiveness is inadequate, primarily focusing on a single performance aspect within the progress of certain projects. For example, assessment boundary for cropping management typically revolve around singular cropping technologies(Harun et al., 2021; Paolotti et al., 2016; Jirapornvaree et al., 2021; Wang et al., 2014a; Wang, 2022a), production efficiency across farms of different scales (Debonne et al., 2021; Borghino et al., 2021; Pradeleix et al., 2022; Zhang et al., 2022a; Zhu et al., 2018), and cropping processes based on different grades or product types (Del Borghi et al., 2014; Tricase et al., 2018). These studies lack a comprehensive understanding on farming system, and these assessment scopes are relatively limited, thus neglecting the martials inputs during the farmland construction stage and the long-term benefits on cropping management. Furthermore, detailed reports on the multi-objective effects and regional contribution rates in different farming systems, particularly concerning improvement pathways, are still lacking. It is worth noting that assessment methodology has been widely applied at present. Notably, life cycle assessment (LCA) was adopted to investigate the changes in environmental impactors, using greenhouse gas (GHG) emission, carbon and nitrogen footprint, reactive nitrogen loss as assessment indicators (Goossens et al., 2017; Câmara-Salim et al., 2021; Wang et al., 2021). Additionally, both cost–benefit analysis (CBA) and life cycle costing (LCC) have been commonly used to estimate economic benefits in agricultural activity (Pena et al., 2022; Saber et al., 2020; Li et al., 2020a). The advancements in assessment methods significantly enhance academic understanding of the relationship between agricultural activities and their environmental–economic impacts, providing a more robust framework for evaluating sustainable development in agriculture.

2 http://www.gov.cn/xinwen/2022-12/14/content_5731827.htm

3 https://www.fao.org/3/cb6872en/cb6872en.pdf

4 https://m.gmw.cn/baijia/2022-12/26/36256469.html

5 http://www.moa.gov.cn/ztzl/2023yhwj/zxgz_29323/202302/t20230214_6420463.htm

6 http://www.moa.gov.cn/hd/zbft_news/qggbzntjsgh/xgxw_28866/202109/P020210916554589968975.pdf

7 http://www.gov.cn/xinwen/2019-03/02/content_5369853.htm

Wheat–maize rotation is a crucial cropping system that has been effectively utilized as a tillage practice to improve soil quality and increase farmers' income in China (Li et al., 2020b; Wang et al., 2014b) . Previous reports indicate that the North China Plain is the largest cropping region employing wheat–maize system, contributing approximately 60% of the country's wheat and 30% of its maize. However, diverse farmland infrastructure and cropping management practices in this region have driven the implementation of numerous agricultural demonstration projects, resulting in the proliferation of diverse farming systems. In this study, to better understand the specific contribution and development dilemma from different farming systems, multiple assessment indicators such as LCA, LCC, CBA, net ecosystem economic benefit (NEEB) and scenario simulation were applied into assessment system. In particular, the farming systems are summarized by exploring the infrastructure requirements for matching the cropping management modes, analyzing environmental–economic benefits from infrastructure construction and cropping management practices, and clarifying the multiobjective effects under wheat-maize cropping. The study's underlying hypotheses are that sustainable farmland and its corresponding farming mode can demonstrate optimal environmental and economic benefits. Additionally, promoting the optimal farming system in major grain regions could effectively mitigate environmental pollution and enhance grain yield.

2. Materials and methods

2.1. Study area and system description

The study was conducted in Yanggu, Ningyang, and Yuncheng counties, Shandong province of China, which is a major grain-producing region located in the North China Plain, and demonstrates apparent differences in farmland production conditions, such as infrastructure facilities and cultivated land quality, thus triggering different cropping management practices. Specially, smallholder farming is still a major mode, although NABE (e.g., large growers, family farms, cooperative organizations, and agricultural enterprises) has developed recently. More intensive and intelligent modes have been introduced into the cropping management measures in the region. Consequently, the region reveals diverse farming systems, which epitomizes the development of farmland infrastructure conditions and cropping management modes in China.

A typical cropping system in this region is wheat-maize rotation, and wheat is sown in mid-October and harvested at the end of May next year. Conversely, maize is sown in early June and harvested in late September. Major agronomic activities in the wheat-maize rotation include tillage, sowing, fertilization, irrigation, plant protection, harvesting, and straw returning. This investigation study was performed during the entire growing season under the wheat–maize crop rotation in 2021. The average temperature is 14.7 °C, and precipitation is 608.6 mm from 2020 to 2021 (Fig. S1).

2.2. Field survey and data collection

The data collection was conducted by randomly visiting households and face-to-face interviewing from September to December 2021 to ensure the accuracy of the collected information. Specifically, 88 smallholder farmers and 38 NABE consisting of 24 farming system II, 14 farming system III were selected, the allocated detail of NABE provided by Table S1. All data on both input and output including economic parameters of the cropping management were recorded in detail, and some data reflecting the martial input of farmland construction, such as design plan, feasibility report and engineering project, estimation, were supplied by the local agricultural administration departments.

2.3. Description of the farming systems under assessment

A total of three farming systems were summarized by profiling the farmland infrastructure condition and cropping management practices. Applied fertilizers include inorganic fertilizer and crop straw, and all parameter differences in different systems are shown in Table S1.

2.3.1. Farming system I: Conventional farmland —Smallholder farming mode (CF-SFM)

The average area of smallholdings is 0.47 ha, and each land plot is only 0.35 ha. The farmland condition is relatively poor, and most of the infrastructure facilities have exceeded or approached their lifespan. Major characteristics of conventional farmland (CF) are uneven land, a lack of machine roads, and outdated irrigation facilities (earth canals). Smallholder management is still dominated by manual labor, while the plowing, harvesting, and straw returning were mainly finished by specific machines, such as the hand tractors used for plowing and tilling as well as special machines used for harvesting and straw returning.

2.3.2. Farming system II: High-standard farmland —Intensive farming mode (HSF-IFM)

Intensive farming mode is usually demonstrated in the cultivated lands that are owned by larger growers, and family farms, and the average area of adopting this mode is 8.56 ha, and the average area per plot is 3.81 ha. Farmlands suitable for intensive management have been incorporated into the first round of HSF construction, and these lands are relatively flat and contiguous, and simultaneously matched with well–developed machine roads, irrigation facilities, and a protective forest network. In the farming process, only fertilization was performed by manual labor, the other planting management measures were completely finished by mechanization operations. All laborers participating in cropping management are often trained and have experience in precision agriculture planting practices.

2.3.3. Farming system III: Sustainable farmland—Efficiency-driven farming mode (SF-EDFM)

Intelligent management is mainly demonstrated in the NABE, especially in those agricultural enterprises and the scaled cooperative organizations, which cultivated 78.67 ha of the land with an area of 30.56 ha per plot. These farmlands were recently constructed to HSF requirements and therefore have better basic conditions. On this basis, the business entity not only improved the facilities used for efficient water-saving irrigation, but also upgraded the standards of machine roads, including widening the roads, using bio-coagulation technology, and implementing permeable surfaces and other eco-friendly designs. Therefore, the farmland infrastructure facilities were well equipped, thus significantly meeting the demands of modern and intelligent agricultural production. Whole cropping activities were operated by mechanization, and drip irrigation was adopted to efficiently reduce water waste. Meanwhile, professional agricultural scientists performed quantitatively precise fertilization and plant protection practices in accordance with the specific requirements of crop growth (concept map of SF- EDFM as shown in Fig. 1, and the other systems map as shown in Fig. S2).

2.3.4. Research hypothesis

Agricultural systems should align with the comprehensive development goals of 'resource conservation, efficient output, and eco-friendliness.' Research indicates that transitioning from traditional smallholder farming practices, driven by experience, can mitigate nonpoint source pollution resulting from excessive chemical inputs (Bruulsema, 2018; Adegbeye et al., 2020; Ren et al., 2023). The adoption of new technologies and advanced production facilities, including integrated water and fertilizer management, physical and biological pest control, and agricultural mechanization, is considered essential for enhancing agricultural resource utilization efficiency (Bijarniya et al.,

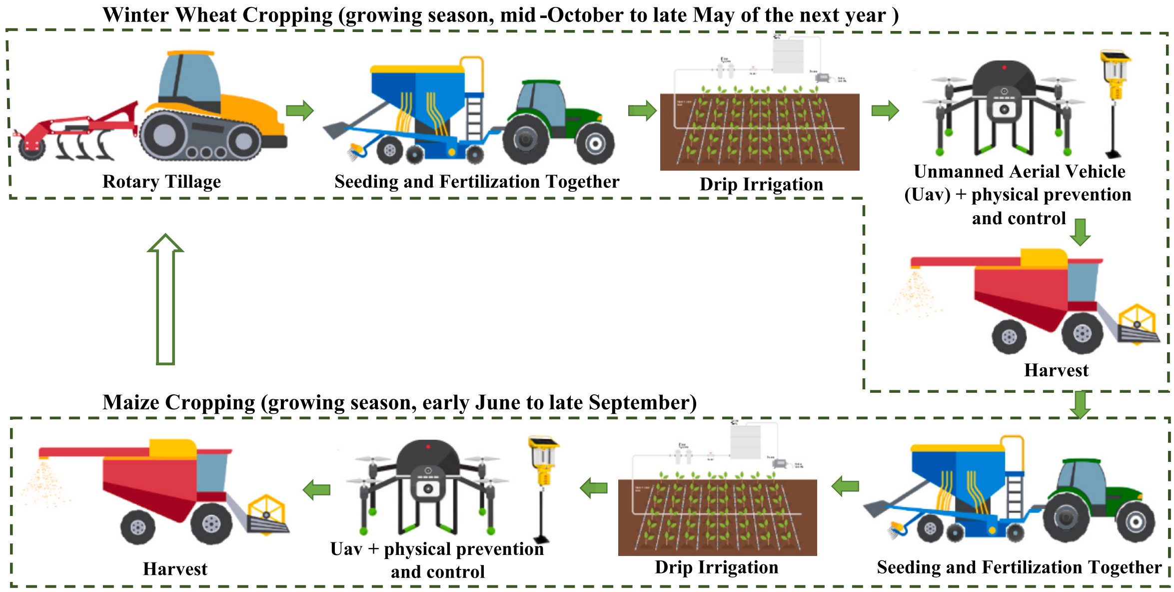

Fig. 1. Farming system III: Efficiency-driven farming mode under sustainable farmland.

2020; Rusinamhodzi et al., 2016; Arunrat et al., 2021; Wang et al., 2014b). Moreover, large-scale farming operations, capitalizing on economies of scale, have the potential to enhance agricultural output and boost farmers' income (Arunrat et al., 2021; Wang et al., 2014b). In summary, achieving sustainability goals in agricultural systems requires standardized and precise management of production, as well as expanding operational scale. Whether through technological innovation or large-scale farming operation, the key lies in excellent farmland infrastructure. Comprehensive and advanced infrastructure is crucial for promoting cropping modes transformation. The characteristics of SF-EDFM in terms of farmland infrastructures and cropping management better align with sustainable requirements. Based on these premises, the following hypothesis is proposed:

Hypothesis 1. Compared to HSF-IFM and CF-SFM, SF- EDFM demonstrates optimal environmental and economic benefits, aligning with the integrated goals of "production-ecology-livelihood" and thus is considered a efficiency-driven farming system.

The most effective approach to promoting a farming system is by highlighting its advantages. In agriculture, establishing demonstration zone is the predominant method for illustrating the benefits of new agricultural products, practices, and modes (Leta et al., 2017; Wang and Cui, 2023; Zhang et al., 2024). Selecting demonstration zone typically requires meeting the fundamental criteria for implementing products, practices, or modes, ideally in areas conducive to maximizing their effectiveness (Adamsone-Fiskovica et al., 2021). Favorable farmland conditions are paramount for demonstrating a farming system, as flat terrain can mitigate the challenges and costs associated with land consolation and infrastructure construction (Qian et al., 2015). Moreover, grain-producing regions play a crucial role in safeguarding national food security, underscoring the importance of establishing demonstration zones in these areas to bolster grain productivity. Recent agricultural policy documents prioritize the development of sustainable farmland in plain terrain with irrigation capabilities.[8] Therefore, the following hypothesis is formulated:

Hypothesis 2. Promoting the optimal farming system in the North China Plain could effectively mitigate environmental pollution and enhance grain yield, thereby ensuring food security and promoting sustainable agricultural development.

2.3.5. System boundary for assessment

System boundaries, along with relevant inputs and outputs of farming systems, were characterized as depicted in Fig. 2. Currently, the farmland construction is government-mediated, while cropping management is performed by agricultural producers, thereby causing inconsistent investment partners at the two stages. Consequently, economic analyses of farming systems, including LCC, CBA, and NEEB, primarily focus on farmland utilization, while construction costs are examined through comparisons of different farmlands. In this study, an assessment framework was developed to evaluate the multi-objective effects of farming systems on production, ecology, and livelihood, aiming to comprehensively understand their integrative impacts.

2.4. Environmental impact assessment

The environmental evaluation includes two stages representing the infrastructure construction of farmland and cropping management.

2.4.1. Infrastructure construction

Material inputs in the farmland construction stage usually significantly affect environmental changes, mainly leading to changes in carbon emissions (Shan et al., 2020). Here, the carbon effect on farmland construction is calculated by the Eq. (1).

$$C_{CP} = \sum_{i=1}^{N} E_i * EF_{CMi} \tag{1}$$

where C_{CP} indicates the total carbon emission during the construction period, E_i means the amount of material and energy input, and EF_{CMi} represents the carbon emission coefficient of materials and energy sources (Table 2).

2.4.2. Cropping management

The inputs required for crop management, including seeds, fertilizers, and pesticides, as well as resource consumption for activities such as fertilization, pest control, irrigation, and mechanized operations resulting from production activities, are listed in Table 1. The

[8] https://www.gov.cn/yaowen/liebiao/202402/content_6929930.htm

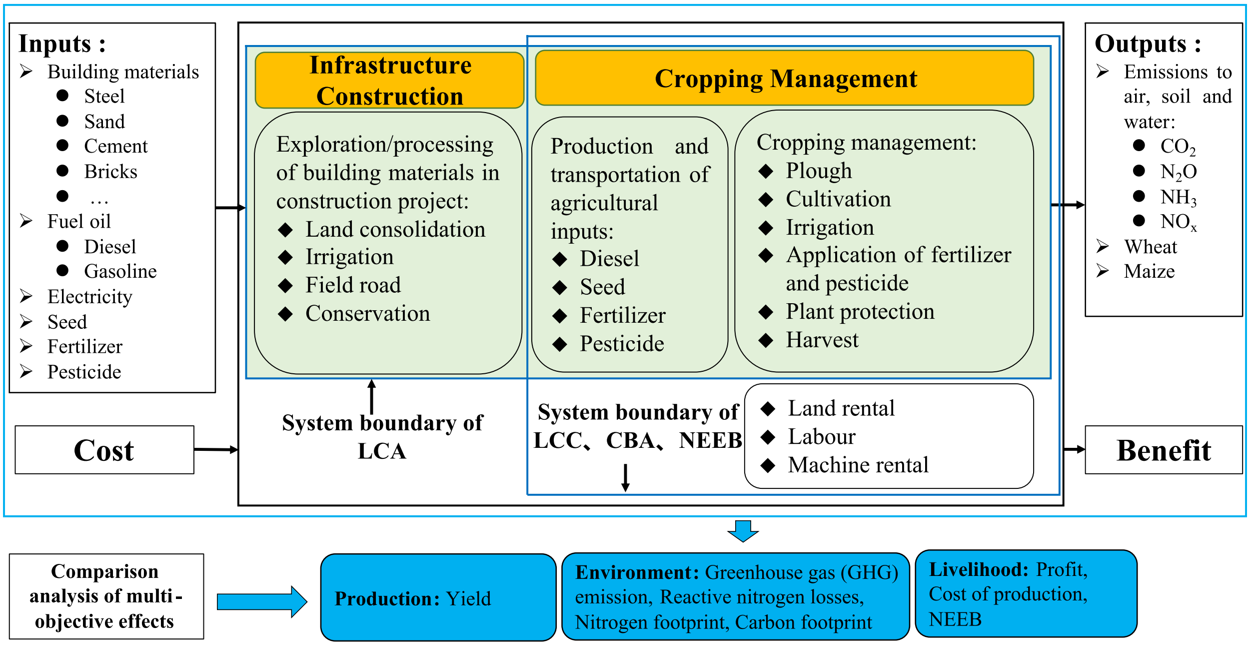

Fig. 2. Framework and system boundary for assessment.

Table 1
Resource input and output.

Item	Wheat cropping			Maize cropping		
	CF-SFM	HSF-IFM	SF-EDFM	CF-SFM	HSF-IFM	SF-EDFM
Inputs						
Seeds (kg/ha)	187.50 ± 2.66	225.00 ± 5.12	273.75 ± 5.50	33.00 ± 2.50	39.00 ± 1.80	45.00 ± 0.89
N (kg/ha)	324.00 ± 5.74	191.25 ± 4.68	180.90 ± 6.42	315.00 ± 4.12	243.75 ± 6.55	252.00 ± 6.96
P (kg/ha)	216.00 ± 3.57	236.25 ± 4.42	180.90 ± 5.21	52.50 ± 4.20	48.75 ± 8.50	54.00 ± 5.23
K (kg/ha)	67.50 ± 8.20	56.25 ± 6.50	50.25 ± 6.84	52.50 ± 6.26	97.50 ± 6.45	54.00 ± 3.10
Pesticide (kg/ha)	8.43 ± 2.73	5.50 ± 1.54	5.00 ± 0.76	15.72 ± 3.06	10.86 ± 1.03	10.00 ± 0.82
Plant protection for electricity (kwh/ha)	–	–	30.00 ± 0.00	–	–	30.00 ± 0.00
Drip irrigation belt (PE pipe) (kg/ha)	–	–	262.50 ± 0.00	–	–	–
Irrigation water (m^3/ha)	1950.00 ± 37.53	1575.00 ± 22.55	1275.00 ± 12.76	1350.00 ± 35.50	1080.00 ± 21.08	900.00 ± 10.54
Irrigation for electricity (kwh/ha)	900.00 ± 28.20	720.00 ± 23.82	450.00 ± 9.01	675.00 ± 24.85	540.00 ± 20.47	360.00 ± 7.50
Diesel (kg/ha)	210.38 ± 12.06	204.13 ± 11.20	173.40 ± 6.50	153.00 ± 11.44	143.18 ± 10.50	105.06 ± 8.22
Labor (h/ha)	204.26 ± 1.20	86.06 ± 2.53	45.00 ± 2.24	178.72 ± 1.20	64.50 ± 2.31	38.00 ± 2.40
Output						
Crop yield (kg/ha)	6501.75 ± 32.20	7582.50 ± 40.13	7500.00 ± 36.50	8167.62 ± 35.24	10,504.88 ± 54.60	10,231.73 ± 50.42

environmental changes in three farming systems were quantitatively compared by LCA, and the system boundary was defined as the whole cropping rotation period of the wheat–maize, including agricultural material acquisition, material application, and mechanical mode in the field. The reactive nitrogen losses include N_2O emission, NH_3 volatilization, and NO_3-leaching which were caused by nitrogen fertilizer application. For accurately assessing the environmental impacts, region-specific empirical factors such as N_2O emission, NH_3 volatilization, and nitrogen leaching were adopted (Zhang et al., 2019), thus revealing the environmental impacts such as reactive nitrogen (Nr) losses, GHG emissions, and energy consumption. The above environmental impacts were expressed by unit area per ha and unit grain mass per ton, respectively.

Greenhouse gas (GHG) emissions from agricultural activities are calculated by Eq. (2):

$$GHG_{emission} = \sum_{i=1}^{n} (Input_i * EF_i) \tag{2}$$

i is the input source, $GHG_{emission}$ is the GHG emission from agricultural production and transportation, energy, and electricity (kg CO_2-eq·hm^{-2}), *Input* is the agricultural material input, and EF_i is the emission factor for agricultural and energy inputs, as shown in Table S2.

The reactive nitrogen losses are calculated by Eq. (3):

$$\text{Nr losses} = N_2O_{direct} + N_{leaching} + NH_3 volatilization \tag{3}$$

For investigating direct and indirect N_2O emissions from fertilization-triggering, Eq. (4) is used for estimating direct N_2O emissions, and indirect N_2O emissions from the deposition of fertilizers usually exist in the form of NH_3 and NO_x, and are calculated by Eq. (5). By contrast, the nitrogen emission from leaching and runoff is calculated by Eq. (6), and the N_2O emission from fertilizer application is calculated by Eq. (7).

$$N_2O_{direct} = [(F_{SN} + F_{CR}) * EF_1] * 44/28 \tag{4}$$

$$N_2O_{(ATD)} = (F_{SN} * FRAC_{CASF} * EF_{2SN}) * 44/28 \tag{5}$$

Table 2
Material input and its carbon emission in construction stage (CS).

Material	Emissions factors	Unit	References	Emission (kg CE)	
				HSF	SF
Diesel	0.862	kg CE/kg	Intergovernmental Panel on Climate Change (IPCC)	469.469	460.856
Gasoline	0.814	kg CE/kg	IPCC	0.004	0.003
Steel	2200	kg CE/t	China Institute of Atomic Energy (CIAE)	98.781	65.781
Sand	1.890	kg CE/m^3	IPCC	13.634	16.489
Cement	843.250	kg CE/t	IPCC	5387.398	6396.599
Bricks	1452.300	kg CE/1000 blocks	IPCC	695.432	1300.288
Gravel	2.250	kg CE/m^3	IPCC	44.483	46.234
Asphalt	238.520	kg CE/t	IPCC	1.916	2.457
Electricity	0.714	kg CE/kg	Guidelines for provincial greenhouse gas inventories (pilot)	1.124	2.761
Quicklime	0.687	kg CE/kg	IPCC	0.303	0.312
PVC pipe	0.860	kg CE/kg	IPCC	0	5.282
Shelter-belts	−23.660	kg CE/per	(Xiangguo, 2010)	−520.520	−567.84

Table 3
Investment standard and carbon emission in CS.

Farmland type	Investment (CNY/ha)	Total carbon emission in CS (kg CE)
Sustainable farmland (SF)	42,600	7729.224
High-standard farmland (HSF)	34,200	6192.026

Table 4
Cost-benefit ratio.

	CF-SFM	HSF-IFM	SF-EDFM
Total cost(CNY/ha)	14,012.30 ± 4.50a	18,691.89 ± 7.69c	18,287.94 ± 5.88b
Profit(CNY/ha)	20,477.58 ± 5.71a	24,424.86 ± 7.46b	25,741.36 ± 8.31c
Cost-benefit ratio (CNY/ha)	1.46c	1.31a	1.41b

Note: Different letters within the same row indicate significant ($p < 0.05$) differences among three farming modes.

Table 5
Financial need and environmental-economic effects promoting the SF-EDFM in the North China Plain.

	Construction Financial need (CNY)	GHG emissions (t CO_2 eq)	Profit (CNY)	NEEB (CNY)	Total grain production (t)
CF (22%)-HSF (52%)-SF (26%)	4.87 E+10	9.67 E+07	5.72 E+10	5.27 E+10	1.47E+04
CF (22%)-HSF (39%)-SF (39%)	4.76 E+09	9.55 E+07	8.58 E+10	7.91 E+10	1.47E+04
CF(0%)-HSF (50%)-SF (50%)	3.55 E+10	9.01 E+07	1.10 E+11	1.01 E+11	1.53E+04

$$N_2O_{leaching} = (F_{SN} + F_{CR})*FRAC_{LEACH}*EF_3*44/28 \quad (6)$$

$$GHG_{N_2O} = \left(N_2O_{direct} + N_2O_{(ATD)} + N_2O_{leaching}\right)*298 \quad (7)$$

N_2O_{direct} is the direct N_2O emissions from soil fertilization (kg N_2O -N·ha^{-1}), F_{SN} is the fertilizer input at each growing season (kg N·ha^{-1}·growing season^{-1}), F_{CR} is the straw return per growing season (straw and underground roots)(kg N·ha^{-1}·growing season^{-1}), EF_1 is the N_2O direct emission factor [kg N_2O -N·(kg $N_{input}$$^{-1}$)], $N_2O_{(ATD)}$ is the N_2O emission from fertilizer volatilization in the form of NH_3 and NO_x-N because of deposition (kg N_2O-N·ha)$^{-1}$, $FRAC_{CASF}$ is the ratio of the volatilized NH_3 versus NO_x-N. $FRAC_{CASF}$=0.1 kg N·kg^{-1} N (NDRC, 2011), EF_{2SN} is the emission factor of the deposited N_2O [kg N_2O·(kg N)$^{-1}$], $N_2O_{leaching}$ is the indirect emission of N_2O from nitrogen fertilizer leaching and runoff (kg N_2O-N·ha^{-1}), $FRAC_{LEACH}$ is the ratio of nitrogen losses by leaching and runoff, $FRAC_{LEACH}$=0.2 kg N·kg^{-1} N (NDRC, 2011), EF_3 is the indirect emission factor of N_2O by leaching and runoff [kg N_2O·(kg N)$^{-1}$], 44/28 is the conversion coefficient of N_2O-N to N_2O, and GHG_{N_2O} is the N_2O emission from fertilizer application (kg CO_2·ha^{-1}), number 298 represents the greenhouse effect equivalent coefficient of N_2O comparing with CO_2 (IPCC, 2014).

A total of GHG emissions from the wheat–maize rotation period is calculated by Eq. (8).

$$GHG_{all} = GHG_{input} + GHG_{N_2O} \quad (8)$$

2.5. Economic impact assessment

2.5.1. LCC and profitability

Generally, LCC could better reflect the costs associated with a product or service, and is directly decided by manual action (Hunkeler et al., 2008). Here, LCC was employed to analyze the costs used for grain cropping, such as fixed costs (e.g., land rent, labor physical payments, the purchase of agricultural inputs, irrigation costs, and machinery rental). Notably, the LCC is only used for assessing the costs of cropping management, correspondingly demonstrating the total cash flow from the producers, but not including the infrastructure depreciation in the calculation. Combined with an economic analysis, the financial performance of the wheat-maize rotation system was determined by using the LCC and the farmland per ha. The cost-benefit ratio is calculated to evaluate the profit of per unit cost in three systems as shown in Eq. (9).

$$Cost_{benefit\ ratio_i} = \frac{Profit_i}{LCC_i} = \frac{Income_i - LCC_i}{LCC_i} \quad (9)$$

$Cost_{benefit\ ratio_i}$ is the cost benefit ratio of agriculture producer i, $Profit_i$ is the difference between general income and LCC from agriculture producer i. $Income_i$ is the general income of agriculture producer i from selling wheat and maize, and LCC_i is the life cost of crops.

2.5.2. NEEB

Generally, effectively assessing the economic feasibility and environmental costs of farming systems is necessary (Bi et al., 2020; Lin et al., 2023). In this study, the costs from agricultural activities and environmental damage were integrated by NEEB to compare the systematic sustainability of the different farming systems, as shown in the following equation:

$$Yield\ gain = Grain\ yield * grain\ price \tag{10}$$

$$Agriculture\ cost = \sum_{i-1}^{n} AM_i * P_i \tag{11}$$

$$EC_{GHG} = \sum_{i=1}^{n} ED_i * P_C \tag{12}$$

where *Yield gain* expresses the gross plantation income per ha, *Grain yield* is the wheat and maize yield per ha, and *grain price* is the locally commercial price of grain; *Agriculture cost* includes agricultural material purchase and field management costs. AM_i is the quantity of the ith agricultural input per ha, and P_i denotes the unit price of input. ED_i reflects the environmental damage of costs-caused by Nr losses, global warming, and so on. P_C means the conversion coefficient of the environmental damage into currency price, and represents the unit environmental cost of 0.029 USD kg^{-1} CO_2 from GHG emissions (Li et al., 2015; Xia et al., 2016).

2.6. Assessment of economic and ecological potential

In the current study, four typical wheat–maize cropping regions in the North China Plain, Hebei, Shanxi, Shandong, and Henan, were selected to profile the economic and ecological potential assessment. A total of these four cropping regions covers 12.2 million ha of farmland, with 70% of it being irrigable farmland,[9] and the HSF amount accounts for >50% of the cultivated land.[10] Therefore, the staged study on farmland development in the irrigable farmland was performed by the farmland construction plans and the related policy target requirements. The scenario simulation including three development stages (Stage 1: 22% CF–52% HSF–26% SF; Stage 2: 22% CF–39% HSF–39% SF; Stage 3: 0% CF–50% HSF–50% SF) was characterized. Specifically, the construction financial needs were estimated in three stages, and the incremental benefits at each stage were analyzed by the assessment system.

3. Results

3.1. Resource inputs and system productivity

The resource inputs of CF-SFM, HSF-IFM, and SF- EDFM systems are illustrated, revealing notable differences. In summary, SF- EDFM exhibits the lowest resource input among the three systems under wheat-maize cropping, while CF-SFM demonstrates the highest resource input (Table 1). The application rate of N-fertilizer was reduced by 32.4% in the SF- EDFM and 32.1% in the HSF-IFM compared to the CF-SFM. Moreover, pesticide application in the SF-EDFM was performed by unmanned aerial vehicles (UAV), resulting in extra 30 kwh per ha in electricity consumption. Additionally, drip irrigation in the SF-EDFM consumed a total of 262.5 kg/ha of drip irrigation belt per year, while irrigation in the HSF-IFM was dominated by pipe irrigation. Drip irrigation saving about 30% of water and pipe irrigation saving about 20% of water compared to the flood irrigation, respectively. In terms of electricity consumption, the SF-EDFM and HSF-IFM systems saved 20% and 50% compared to the CF-SFM, respectively, resulting in the SF-EDFM consuming the lowest energy. Furthermore, both the SF-EDFM and HSF-IFM demonstrated a significantly lower labor input compared to the CF-SFM.

Statistics show that the HSF-IFM achieved the highest average grain yields of 7.6 Mg ha^{-1} of wheat and 10.5 Mg ha^{-1} of maize, followed by 7.5 Mg ha^{-1} of wheat and 10.2 Mg ha^{-1} of maize in the SF-EDFM, while the CF-SFM yielded the lowest grain yields of 6.5 Mg ha^{-1} of wheat and 8.2 Mg ha^{-1} of maize.

3.2. Result of environmental benefits

3.2.1. Carbon effect in farmland construction

GHG emissions during the construction stage in the SF amounted to 7.7 t CE/ha, representing a 1.5 t CE/ha increase compared to the HSF (Table 3). This increase can be attributed to relatively higher material inputs in the SF, reflecting efforts to enhance farmland productivity. Consequently, without integrating the analysis with cropping practices, the HSF appears to be more conducive to achieving carbon reduction goals. Since both land reclamation and ditch digging in the CF were mainly finished by manual labor in 1970s, with relatively limited material inputs used for construction, therefore, the GHG emissions from the CF were not estimated in the study.

3.2.2. Reactive nitrogen losses, nitrogen and carbon footprint, GHG emissions of cropping management

The analysis results indicate that environmental indicators of the CF-SFM are significantly higher than those of other systems. Both SF-EDFM and HSF-IFM exhibit similar levels of active nitrogen loss and nitrogen footprint, whereas SF-EDFM demonstrates lower GHG emissions and carbon footprint compared to HSF-IFM. Therefore, SF-EDFM demonstrates the best environmental performance, followed by HSF-IFM, while CF-SFM exhibits poorer outcomes (Fig. 3). Besides, NO_3-leaching was found to be a critical factor affecting nitrogen losses and nitrogen footprint. The components of GHG emissions, such as chemical input in cropping, transportation, and field application, greatly contributed to nitrogen emission increases, followed by electricity and fuel consumption. Although the contribution ratio from various components was relatively consistent in different systems, the contribution magnitude significantly varied. It is observed that all components in both the SF-EDFM and HSF-IFM almost had no significant negative effects, only the CF-SFM showed the strongest negative effect. Furthermore, the data confirmed that the different systems demonstrated obvious differences in the quantity and type of resource input.

3.3. Economic benefit by LCC, CBA and NEEB

HSF-IFM had the highest cropping costs of 18,691 CNY/ha, followed by the SF-EDFM with 18,287 CNY/ha, while CF-SFM had the lowest costs of 14,012 CNY/ha (Fig. 4 (a)). Data indicates that agricultural materials, such as seeds, fertilizers and pesticides, accounted for the highest portion of the input costs. Besides, costs associated with mechanical application also occupied a significant portion. Unlike agricultural materials, costs related to labor employment and land rent in both SF-EDFM and HSF-IFM were largely determined by farming scale. Surveys found that land rent in SF-EDFM or HSF-IFM reached 4500 CNY/ha, maintaining a moderate level in the Yellow River Basin due to local agricultural policy reasons. Additionally, SF-EDFM controlled pests by physical measure, leading to increased energy expense, such as utilization of pest control lights.

The cost-benefit analysis shows that SF-EDFM revealed the highest profits of 25,741 CNY/ha, followed by HSF-IFM with profits of 24,425 CNY/ha, while CF-SFM had the lowest profits of 20,478 CNY/ha (Table 4). However, the cost-benefit ratio CF-SFM at 1.461 was higher than that of HSF-IFM at 1.31 and SF-EDFM at 1.41. SF-EDFM exhibited the highest NEEB of 23,792 CNY/ha, followed by the HSF-IFM with 22,136 CNY/ha, while the CF-SFM showed the lowest NEEB of 17,711 CNY/ha (Fig. 4(b)).

[9] http://www.stats.gov.cn/tjsj/ndsj/2022/indexch.htm
[10] https://www.idpi.cn/gongzuoxindetihui/2169470.html

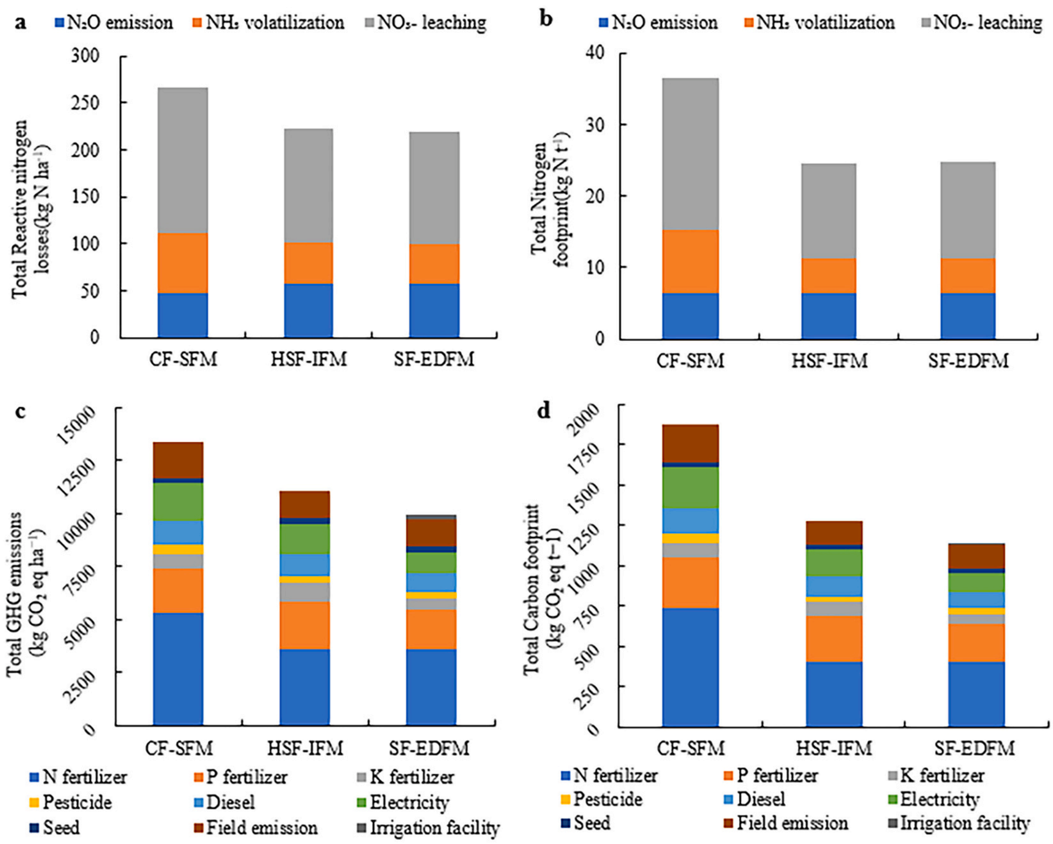

Fig. 3. Reactive nitrogen losses (a), nitrogen footprint (b), greenhouse gas emissions (c), and carbon footprint (d) under wheat-maize rotation in three systems.

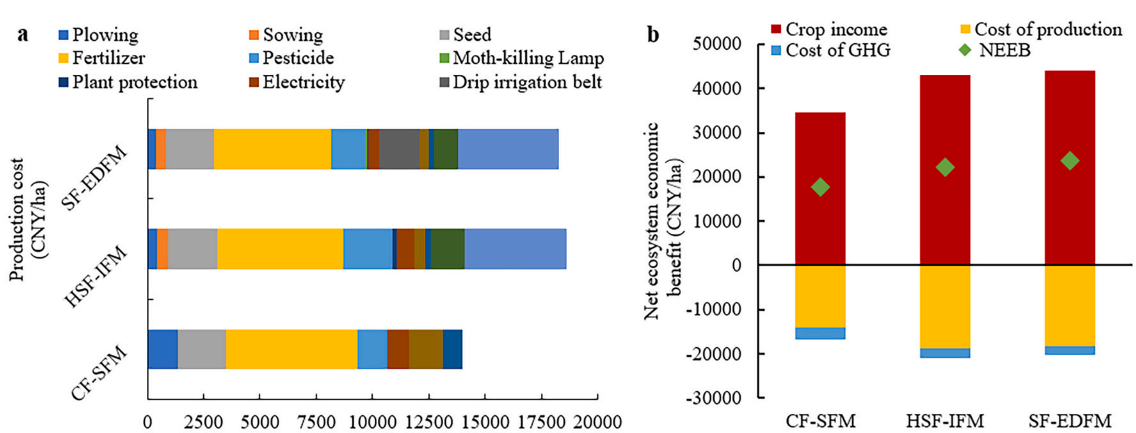

Fig. 4. Cost of wheat-maize cropping under three systems (a); NEEB of three systems (b).

3.4. Prospects of SF-EDFM

Integrating the environmental and economic analyses showed that SF-EDFM was more aligned with the target of sustainable agricultural development. This assertion is supported by several factors: 1) SF-EDFM achieves relatively high yields with minimal resource input and retains the potential for further output increases under current resource input standards. This aligns perfectly with the profound connotations of sustainability, namely resource conservation and efficient output. 2) SF-EDFM exhibits the most prominent environmental and economic advantages, showing the integration of eco-friendly development principles into the farming system and enhancing its sustainability. 3) large growers, family farms, cooperatives, and agricultural enterprises are identified as the most suitable operational entities for adopting SF-EDFM, aligning with current strategies aimed at accelerating the cultivation of NABE to promote large-scale agricultural operations. It has emerged as a crucial pathway for transforming the landscape of smallholder farming[11],[12] Based on these considerations, the anticipated hypothesis is confirmed, and SF-EDFM is regarded as a efficiency-driven farming system. Considering the realities of farmland construction and agricultural development in China, achieving a 1:1 ratio of HSF to SF

[11] https://www.gov.cn/zhengce/zhengceku/2022-03/29/content_5682254.htm

[12] https://www.gov.cn/zhengce/2016-05/25/content_5076559.htm

through three stages is targeted.[13] The total estimated construction costs amount to CNY 8.84 billion (Table 5), enabling the realization of goals such as reducing emissions by 9.01E+07 (t CO_2 eq) and increasing profits by CNY 110 billion along with a NEEB of CNY 101 billion. Importantly, these regions could potentially increase grain production by 1278 t, as depicted in the benefit potentials presented in Fig. 5.

4. Discussions and implications

Improving infrastructure and transforming cropping management practices are essential steps in the development of SF system. Previous studies have highlighted that improving infrastructure contributes to ensuring food security and adopting environmentally friendly agricultural production practices (EFAPP), which mitigate the environmental impacts of agricultural activities (Zeweld et al., 2020; Martinho, 2019; Yin et al., 2022; Zhang et al., 2022b). At present, CF-SFM, HSF-IFM, and SF-EDFM are the three main farming systems. Among them, only the SF-EDFM demonstrated the optimal environmental–economic effect, followed by the HSF-IFM, but the CF-SFM had a remarkable efficiency difference compared with the other systems. However, CF occupies 66% of cultivated land, with 70% being farmed by smallholders. HSF-IFM is in a transitional state between CF-SFM and SF-EDFM, revealing more universality in agriculture production. While HSF construction has reached a peak to a certain extent, progress in adopting EFAPP has been advanced. Consequently, recognizing and promoting the superiority of SF-EDFM through pilot demonstrations (Fang et al., 2021; Wang, 2022b), is crucial for further enhancing agricultural transformation. However, as the promotion of SF-EDFM has not yet established an absolute advantage, gradually achieving the goals of 'food security, farmland ecology health, and farmer prosperity' through the improvement of different farming systems remains a core objective. Our study elucidates the reasons for the disparities in benefits among different farming systems, proposing specific improvement pathways to address these differences.

4.1. *The role of SF-EDFM in optimizing resource input and improving its productivity*

Analysis demonstrates that SF-EDFM had the lowest resource input. Several factors contribute to this observation. Firstly, SF benefits from well-developed infrastructure and relatively flat land, making it more conducive to mechanized and facilitated agricultural activities. Secondly, large-scale farming is a major characteristic of SF-EDFM. Research has shown that small and scattered land plots decrease machinery efficiency, leading to increased fuel consumption and machinery loss (Valtiala et al., 2023; Bradfield et al., 2021; Zhang et al., 2021). Finally, the specialization degree of farmland managers plays a crucial role in adjusting and executing production practices (Mc Fadden and Gorman, 2016; Yang et al., 2022). Interviews revealed that smallholder farming traditionally relies on experiential knowledge but lacks the specialized technical training. Consequently, smallholders tend to apply excessive amounts of seeds, fertilizers, pesticides, and other materials, leading to higher input costs compared to standard requirements (Nziguheba et al., 2016; Mengistie et al., 2017; Ren et al., 2021). Moreover, smallholders often struggle to innovate agricultural technology, materials, and facilities (Rada and Fuglie, 2019), and face challenges in accessing introduction channels and adopting new production practices (Li et al., 2021; Zhao et al., 2022). Therefore, expanding the scale of cropping on farmland and developing adequate infrastructures are very important task that require guidance for agricultural producers and the establishment of standard farmland infrastructure construction policies. To achieve this target, land transfer action has been conducted to support large-scale farms in China[14,15] Meanwhile, improving and innovating the technical skills of agricultural producers through training programs is essential. Strengthening farmers' professional knowledge can enhance their willingness to engage in large-scale farming (Sutherland et al., 2017; Taylor and Bhasme, 2018; Xia et al., 2017).

Investigation found that the productivity in SF-EDFM was lower than that in HSF-IFM due to greater losses in seeds, fertilizers and crop grains from mechanical work in the former (Qu et al., 2021). Additionally, SF-EDFM is usually managed by agricultural enterprises or cooperative organizations, which often overlook cropping management practices. Although the professional agronomists are employed, the increases in grains yields are still limited because of lacking accountability. In contrast, HSF-IFM is basically managed by the larger growers, cropping cooperative units, and family farms, where agricultural production is the primary source of income. This family-oriented mode of production focuses on intensive farming, resulting in higher crop yields. As for CF-SFM, obsolete farmland endowment and non-standardized farming practices seriously limited productivity relative to the other systems, indicating the urgent need to improve infrastructure and develop the standardized production specification. Agricultural administration should deploy specialized agronomists to provide guidance on applying innovative technology and implementing scientific cropping management practices for smallholders. Furthermore, local agricultural administration departments can motivate NABE participation by organizing grain productivity competition and supervising cropping practices. The governmental agency should also positively develop the publicity education activities to enhance the agronomist's sense of responsibility.

4.2. *The contribution assessment on SF-EDFM in response to the environment-friendly agriculture*

Obviously, HSF showed lower carbon emissions than SF during the farmland construction stage, primarily because SF required advanced farmland infrastructure and relatively more construction materials. Interviews indicated that the service life of SF's infrastructure could be extended by 5–8 years, with maintenance cost was reduced by 10%. Although these data require further verification, SF provided more convenient conditions for agricultural production, facilitating the increased application of innovative technologies and yielding positive environmental benefits. At present, all industries are implementing stricter environmental standards to achieve the goal of "carbon peaking and carbon neutrality" (Albrizio et al., 2017; Lieder and Rashid, 2016; Zhang et al., 2022c), necessitating the minimization of material inputs during farmland construction. Additionally, the use of new environmentally friendly materials presents a promising pathway for optimizing building materials (Sangmesh et al., 2023; Xu et al., 2022), thus offering valuable support for improving the SF system.

Previously reported, SF-EDFM is considered as a symbol of environment-friendly agriculture due to its lower resource input and adoption of environment-friendly production practices in cropping, with agricultural material quantities also being subjectively controlled by producers (Zhang et al., 2023b). The study shows that various low-efficiency practices in agricultural production easily led to the resources waste and increased the GHG emissions (Gołaś et al., 2020; Hou et al., 2020). Generally, differences in machinery application primarily result in environmental effects due to variations in fuel consumption types across different machines (Houshyar and Grundmann, 2017; Li et al., 2012). In particular, field survey shows that machinery with low fuel consumption requires higher purchase expenses, typically affordable for agricultural businesses or machinery cooperatives, thereby highlighting the importance of promoting energy-efficient machinery to

[13] http://www.moa.gov.cn/hd/zbft_news/qggbzntjsgh/xgxw_28866/202109/P020210916554589968975.pdf

[14] http://www.gov.cn/gongbao/content/2014/content_2786719.htm

[15] http://www.gov.cn/gongbao/content/2021/content_5600084.htm

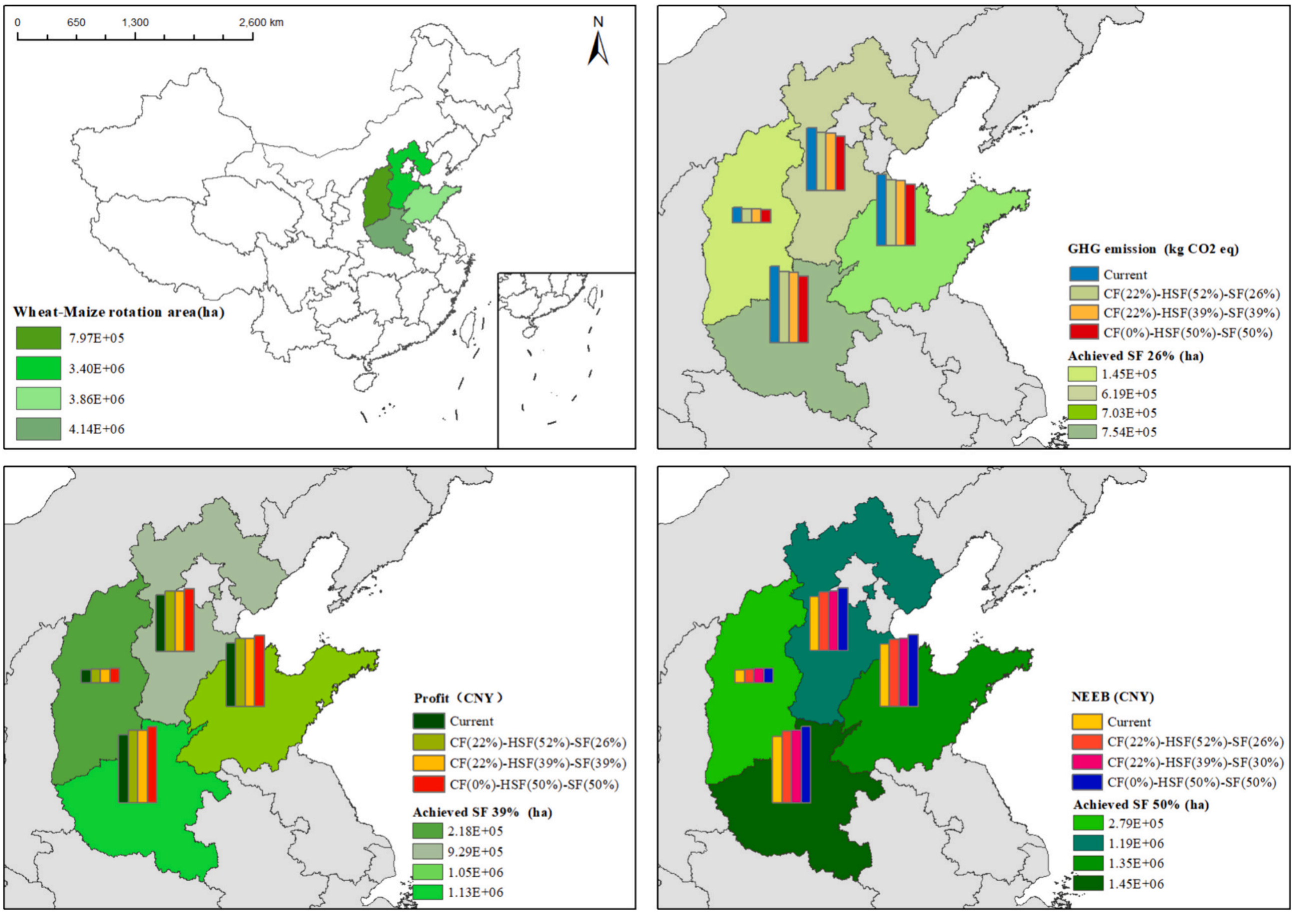

Fig. 5. Benefits potential promoting the SF-EDFM in the North China Plain.

address this dilemma. Moreover, electricity consumption is considered a key factor affecting environmental performance, mainly due to its association with irrigation systems (Huang et al., 2021), with drip irrigation in the SF-EDFM being one of the most water and electricity saving methods (Surendran et al., 2016; Yahyaoui et al., 2017; Li and Xu, 2022). However, drip irrigation technology is not widespread in the cropping, and that requires a better land flatness, and the renovation project is a complicated process and relatively cause higher costs, thus lowering the willingness of investing the agricultural production. Furthermore, even with support from relevant projects, agricultural producers exhibit reluctance to adopt this renovation, indicating a lack of knowledge about technology addressing operational difficulties and maintenance costs (Luo et al., 2021; Xu et al., 2018). In general, agricultural machinery purchase subsidies should be extended and optimized in China,[16] considering different machinery types and formulating reasonable subsidy ratios for various agricultural producers. In addition, the government should pay more attention on supporting resource-saving, environmentally friendly facilities and technologies, guiding NABE to share infrastructure construction cost. Administration division should provide detailed training on the application of environment-friendly technology, emphasizing its benefits to promote agricultural operators' willingness to adopt new technology. Furthermore, a reasonable subsidy mechanism would be more conducive to producers' enthusiasm for technology adoption during technology diffusion (Knierim et al., 2019; Li et al. (2022).

4.3. SF-EDFM prevails in economic performance

CF-SFM has demonstrated the lowest production cost, while HSF-IFM has a higher cost than SF-EDFM. This difference arises because CF-SFM largely relies on the labor inputs of smallholder farmers, resulting in reduced expenses related to hiring machinery and labor. Meanwhile, smallholder farming rarely adopts innovation agricultural technology to reduce the costs in technical innovation at present. In contrast, both HSF-IFM and SF-EDFM reveal high levels of mechanization and modernization, along with widespread adoption of water-saving irrigation and environmentally friendly pest control techniques. However, farming scale remains a significant factor contributing to cost disparities (Omotilewa et al., 2021), as supported by the LCC results. These findings suggest that the lowest cost observed in the SF-EDFM could be attributed to a comparison of individual inputs. It is noteworthy that expenses related to agricultural materials comprise the largest proportion of input costs. Therefore, encouragement of large-scale farming and government intervention in the agricultural market is warranted, along with the formulation of relevant agricultural subsidy policies to alleviate the burden on smallholder farmers.

The results confirm that the SF-EDFM not only yielded the highest benefit but also achieved relatively higher yields. Conversely, scaled agribusiness and large cooperative units typically possess ample storage facilities, thereby eliminating limitations on the sale of agricultural products in terms of space and time. Consequently, we suggesting that the construction of storage facilities for agricultural products in the form of a village or town should be seriously introduced into the agribusiness system. Meanwhile, a dynamic announcement platform publicizing the prices of agricultural products should be established to better understand the sale market for agricultural producers.

[16] http://journal.crnews.net/nybgb/2021n/dssq/tzjd/935154_20210511102626.html

4.4. SF-EDFM is necessary for developing high efficiency

It is suggested that SF-EDFM could significantly contribute to the environmental and economic aspects of the agricultural system in the North China Plain, as demonstrated in scenario analysis. Relevant study has highlighted the importance of various factors in the development of SF, including land consolidation, construction of machine roads, and the implementation of water-saving facilities during the construction stage (Asiama et al., 2021; Asimeh et al., 2020; Wang, 2022b). Moreover, energy-efficient machinery and EFAPP are considered as essential components for the development of the SF ecosystem (Aroonsrimorakot et al., 2021; Yin et al., 2022). Our investigation indicates that SF-EDFM exhibited excellent efficiency in the multi-objective comparative analysis (Fig. 6). The coordinated promotion of SF's infrastructure construction and transformation of cropping management has achieved a synergy effect, surpassing the sum of its individual components, thereby enhancing the efficiency of sustainable agriculture transformation. Furthermore, conducting SF pilot demonstrations aligns with the multi-objective needs in sustainable development. However, the current policy appears to neglect suitable operators for SF-EDFM. Due to factors such as an aging labor force and limited capital endowment, policies aimed at transforming smallholder farming have relatively limited effects (A, J. M.P, et al., 2018; Grzelak et al., 2019; Lu and Xie, 2018; Wei et al., 2021). Agribusiness and cooperative units are well-suited for SF-EDFM, suggesting that efforts to cultivate NABE should focus on becoming leaders in developing SF-EDFM.

5. Conclusions

Smallholder farming plays a significant role in China's grain production. However, challenges such as poor infrastructure, fragmented land, and limited capacity among smallholder farmers hinder the adoption of innovative technologies. Additionally, unlocking the potential land productivity remains challenging, and outdated techniques in smallholder farming contributes to increased environmental cost. To address these challenges, a series of actions were developed by constructing the HSF and promoting the EFAPP, and the SDGs received increasing attention from the Chinese government to realize the commitment of "carbon peak and carbon neutral" as an urgent task. In response, the development of SF has been proposed, with local agricultural administration departments encouraged to conduct demonstration activities. In this context, assessing multi-objective benefits are beneficial to understanding sustainable agricultural development and identifying optimization pathways. LCA is a better pathway profiling the environment impact from agriculture activities. Combining LCC and CBA reveals the economic contributions of different farming systems. However, there has been less focus on the effect of farmland type on agricultural production and the impact of farmland construction materials. This study apparently contributes to enriching current assessment methods on farming systems. Firstly, three farming systems (CF-SFM, HSF-IFM, and SF-EDFM) are summarized by a matching form of farmland infrastructure condition and cropping management. Subsequently, the resource input, productivity, environmental benefits, and economics of different farming systems were quantified and compared. The multi-objective benefits data shows that the SF-EDFM is an optimal choice by simulating the contribution potentials. Finally, this study deeply explores optimization pathways for improving farming systems and provides a policy-making reference for assessing sustainable agriculture development (Fig. S3).

It is imperative to acknowledge and account for the constraints

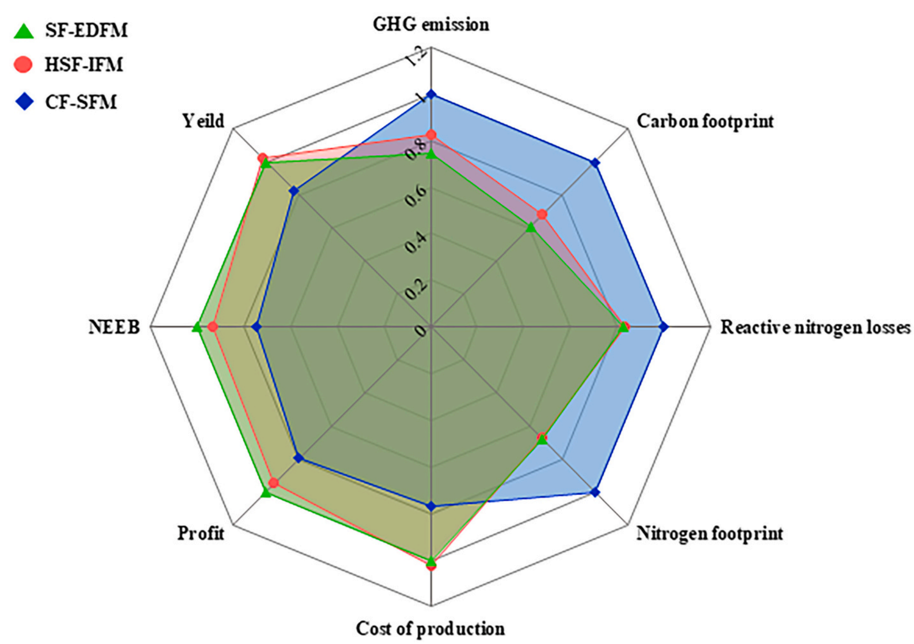

Fig. 6. Comprehensive multiple-objective comparison under wheat-maize cropping in three systems.

inherent in this study. First, the case data only represented the typical modes under the wheat-maize cropping system in the North China Plain and did not reflect the characteristics and performance under the other cropping systems in the other regions, suggesting that expanding study cases with diverse cropping systems is necessary for selection, thus completely improving the systematic evaluation in the future study. Second, based on the IPCC analysis, the environmental impact factors related to the "carbon" should be considered. Although other impact categories can be estimated, experimental and monitoring data should be used to obtain more precise results in future studies. Finally, a wide investigation representing the various farmland and cropping management modes is of great importance, thereby optimally supplementing the other niche modes and accelerating the transformation process of agricultural sustainability.

CRediT authorship contribution statement

Yanshu Yin: conceptualization, questionnaire development, methodology, data curation, software, formal analyses, writing the original draft, visualization, writing reviews and editing, and validation. **Changbin Yin:** supervision, investigation, writing the original draft, resources, project administration, and funding acquisition. **Thomas Dogot:** co-supervision, project administration, validation. **Yang Zhang:** fund acquisition, validation. **Yingnan Zhang:** data curation, writing—review and editing. **Shu Wang:** data curation, software, writing—review and editing. **Ke Xu:** formal analysis, writing—review and editing, data visualization.

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.agsy.2024.104049.

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Further-reading

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