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Evaluation of comprehensive benefits and the degree of coupling coordination for soil health products: a case study in Weifang City, China

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Evaluating the economic, social, and environmental benefits and coupling coordination of soil health products (SHPs) is required for rational soil science management and sustainable agricultural development. Therefore, this paper developed a comprehensive evaluation index system for Weifang City, Shandong Province, China, with the natural breakpoint method and a coupling coordination model to estimate the comprehensive benefits and coupling coordination of SHPs from 2018 to 2021. The comprehensive benefit scores exhibited a generally upward trend over time and regional spatial heterogeneity. However, the economic benefit scores were higher and more closely related to the planting goals of farmers, while the social benefit scores exhibited less fluctuation and lower regional heterogeneity, and the environmental benefit scores were low. In terms of the degree of coupling coordination, the economic, social, and environmental benefits of SHPs were found to be barely coordinated and on the verge of disorder, with distinct spatial distribution characteristics. The disorder of each system was affected by multiple compound factors and significant uncertainty. The results of the present study thus provide a theoretical foundation for decision-making by government and agricultural organizations regarding the use of SHPs.

Keywords Soil health product, Comprehensive benefit, Coupling coordination, Spatial feature

Soil health is required for sustainable development because it guarantees global food security. However, according to *the National Soil Contamination Survey Bulletin*, agricultural production activities in China have polluted farmland soils. Sewage irrigation, the excessive use of agricultural inputs such as fertilizers and pesticides, and intensive livestock and poultry farming all negatively impact the fertility of farmland soils. Science-based soil management practices are thus required to restore the ecological function of soils and safeguard the food supply. In this context, soil health products (SHPs) are a collection of products such as bio-fertilizers, organic fertilizers, soil conditioners, and microbial fungicides designed to promote ecological restoration and health management[1]. SHPs can be used to reduce the bulk density of soils, increase the resistance of crops to disease and pests, improve the internal structure of soils, increase soil aggregates, and improve soil fertility, thus promoting the healthy growth of crops and effectively reducing the pollution of rural surface sources[2]. Therefore, SHPs are an essential component of agricultural green development and the broader goal of sustainable development.

Though SHPs are beneficial to soil restoration, their use in agricultural practices needs to be promoted further. For example, the importance of SHPs in improving soil quality and crop yields needs to be impressed by farmers because soil conditioning and restoration are long-term processes, and their effects are generally not observable in the short term. Long-term systematic validation of the effects of SHPs is also required to overcome the skepticism of farmers regarding their effectiveness. Therefore, evaluating the comprehensive benefits of SHPs and coordinating the relationship between the benefits of the associated economic, social, and environmental subsystems has become a recent focus of the soil science community.

The economic, social, and environmental benefits of SHPs are connected and can be mutually promoted. Soil health is a function of the coupling mechanisms associated with the natural ecological, economic, and social

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systems (Fig. 1) and the synthesis of the recycling of soil resources and improvements in economic efficiency[3,4]. In terms of economic benefits, the regional use of SHPs can improve the structure and nutrient levels of soil, thus increasing crop yields and quality[5]. For example, soil conditioners can increase the organic matter content of the soil, stimulating plant growth and nutrient uptake while improving crop resistance to pests and disease by reducing human and material inputs. The higher crop yields and lower input of pesticides can increase revenue in the agricultural market and improve economic efficiency. At the same time, SHPs companies need to recruit more technicians, production workers, and sales staff to ensure product quality while driving the development of upstream and downstream industry chains.

In terms of social benefits, SHPs can bolster food security by improving soil health, thus ensuring the stable production of crops, vegetables, and fruits, reducing fluctuations in yields due to soil degradation, and meeting the growing demand for food[6]. In addition, the use of SHPs can increase the content of vitamins, minerals, and other nutrients in agricultural products while also improving the taste and flavor. This not only meets consumer demand for high-quality agricultural products but also helps to improve public health and reduce cases of malnutrition. Employing SHPs can also promote employment levels and the development of rural areas, increase the market competitiveness of agricultural products, transform the reliance of rural areas on single-agriculture production to a more diversified industrial structure, and strengthen the risk resistance of the rural economy.

SHPs also have several environmental benefits, such as improving the soil environment, increasing the number and types of beneficial microorganisms in the soil, maintaining the balance and stability of the soil ecosystem, and improving the self-repairing capacity of soils[7]. The rational use of SHPs can also reduce the pollution levels of soil by absorbing heavy metal ions, thus reducing their mobility in the soil and reducing the risk of crop contamination. In addition, the use of SHPs can increase the organic matter content and carbon sequestration capacity of soils[8]. These benefits can contribute to reducing the carbon dioxide concentration in the atmosphere and mitigating global climate change.

In investigating the comprehensive benefits of SHPs, previous studies have mainly focused on soil conditioners, organic fertilizers, and other health products and their environmental, ecological, economic, and social benefits[9]. These results have provided objective references for the evaluation of the comprehensive benefits of SHPs. For example, the effects of different dosages of calcium, potassium, and magnesium soil conditioners on potato yields have been explored, with the results indicating that potato yields and the commercial rate increased by 11.9–21.1% and 14.1–20.9%, respectively, with the soil conditioners promoting the absorption of nutrients and improving the utilization rate of nitrogen fertilizers[10]. In addition, the use of soil conditioners has been shown to effectively inhibit the absorption of *Cd* from the soil by rice plants and reduce the *Cd/Zn* ratio, significantly reducing the *Cd* content of brown rice and lowering the health risks for the local population[11]. In another study, it was suggested that, to establish a social benefit evaluation system for eco-agriculture, it is important to consider factors such as Engel's coefficient and the health and education level of the rural population[12].

In terms of environmental and ecological benefits, different doses of organic fertilizers and soil conditioners have been observed to positively affect maize fertility and yields and the salinity of mildly saline soils. It was thus concluded that both the scientific application of SHPs via rational fertilization and the crop's nutritional

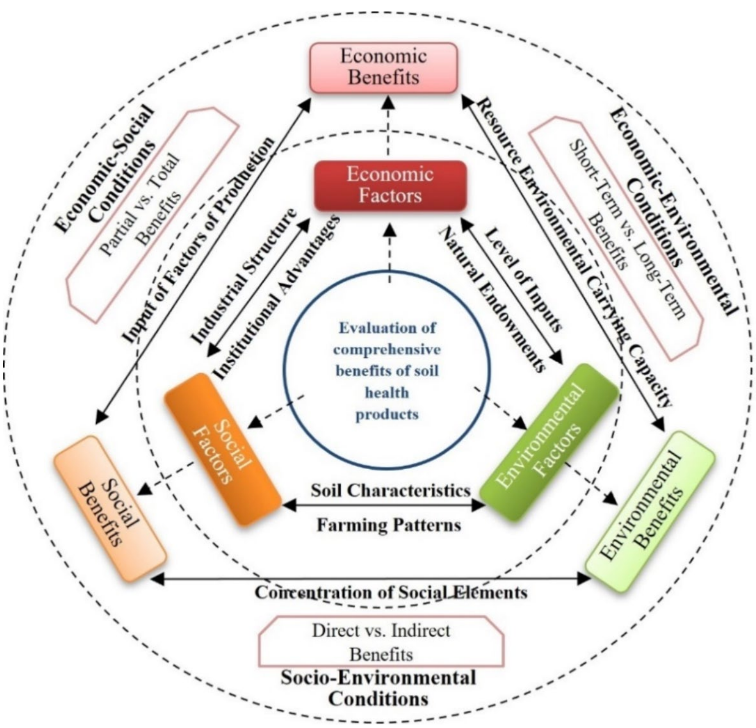

Fig. 1. Coupled mechanisms for the economic, social, and environmental benefits of SHPs.

needs need to be considered[13]. In addition, the migration of soil phosphorus and nitrogen from farmland to water bodies in surface runoff can lead to the eutrophication of surface water, meaning that improving fertilizer application methods can effectively prevent this loss of phosphorus and nitrogen and protect the water bodies around farmland[14]. High-resolution remote sensing data has also been combined with a microscopic analysis of soil and plants to demonstrate that soil erosion strongly affects soil fertility[15].

Various research methods have been developed for the evaluation of comprehensive benefits in various fields, including hierarchical analysis, the entropy value method, principal component analysis, gray correlation evaluation, and projection tracing, each of which has specific strengths and weaknesses[16–18]. For example (Table S1), hierarchical analysis is a decision-making method that decomposes elements related to decision-making into objectives, guidelines, and programs and conducts qualitative and quantitative analysis. It is systematic, can decompose complex problems into multiple levels for analysis, and can effectively deal with problems that are difficult to analyze quantitatively. However, the influence of subjective factors is significant, and the construction of the judgment matrix relies on the subjective judgment of experts, which may lead to bias. The computational burden is also significant, especially when the hierarchical structure is complex, while the consistency test is sometimes difficult to pass, and the judgment matrix needs to be adjusted repeatedly.

Though previous studies on the evaluation of the benefits of SHPs have obtained useful results, there is still scope for further development. In particular, the concept of SHPs needs to be defined in more detail, while more attention needs to be paid to the soil environment and the improvement of the quality of agricultural products. There has also been no differentiation between the economic, social, and environmental benefits for soils in the evaluation of the comprehensive benefits of SHPs. In addition, more research is needed on the construction of comprehensive soil environment management indicators. Past research has mainly centered on theoretical analysis, meaning that the results are highly theoretical and lack practical verification supported by field data. Few empirical studies have been conducted on soil restoration materials to assess their comprehensive benefits.

For these reasons, in the present study, we constructed an evaluation index for the comprehensive benefits of SHPs in the prefecture-level city of Weifang in cooperation with Stanley Agriculture Group Co., Ltd. and other units. By analyzing the evaluation results for their economic, social, and environmental benefits, the spatial divergence in the comprehensive benefits of SHPs in different study areas was identified. The degree of coupling coordination between these benefits in different regions was then measured, and the regions with lower scores were analyzed to explore possible factors associated with the lag in benefits observed in these areas. Finally, we developed suggestions for the optimization of SHPs, thus providing a theoretical reference for the scientific management of soil health in other regions.

Materials and methods

Summary of the study areas

As a center of agricultural industrialization, Weifang City has played a significant role in China's agricultural and rural development[19]. Weifang is in the western region of the Shandong Peninsula, with an area spanning from longitude 118°10'–120°01′E to latitude 35°41′–37°26′N (Fig. 2). With access to 1.7‰ of the land and 1‰ of the fresh water in China, Weifang accounts for 7.2‰ and 15.7‰ of grain and vegetable production, respectively, making it an essential food production base[20]. In a review of previous literature[21], we found that the dominant Weifang soils were brown, lime concretion black, fluvo-aquic, and coastal saline soils, with their distribution and quality influenced by the combination of climatic conditions and geological and hydrological factors (Table 1).

For example, brown soil is found in some areas of Weifang with a high slope, leading to severe soil erosion and lower soil fertility. However, in the central and southwestern areas, the fertility of brown soil is high due to higher fertilizer use and water retention and it is suitable for a variety of crops. Fluvo-aquic soil is present where the terrain is flat and the water supply is sufficient, thus the soil is fertile and important for agricultural production. Lime concretion black soil has a viscous and heavy texture, which needs to be improved to increase the soil quality. Similarly, the coastal saline soil area needs to be desalinized and improved for agricultural production.

Agricultural production in Weifang is the result of strategies promoting green agricultural development and intelligent agriculture. In May 2018, the Weifang government announced *the Weifang Soil Pollution Prevention and Control Work Program*, which prioritizes soil ecological restoration, emphasizes the rational use of chemical fertilizers and pesticides, increases the use of organic fertilizers, and promotes the development of soil health governance and restoration.

Weifang employs professional agricultural cooperatives to unify production standards, supply agricultural inputs, technical services, quality testing, and brand packaging, and promote sales. These measures affect the evaluation framework for the comprehensive benefit of SHPs developed in this paper.

Assessing the comprehensive benefits of SHPs in Weifang has the potential to provide a reference framework for other regions. In particular, the assessment results would help other regions to understand the effectiveness and applicability of SHPs under similar climatic, soil type, and agricultural production conditions. In addition, the results could be used by other governments when formulating relevant agricultural policies, such as subsidies and extension policies, to promote the use of SHPs. Finally, SHPs producers and sellers can use the results as a marketing tool to assist them in promoting their products in other regions.

Data sources

With the permission of our partner organizations, we used eight areas (i.e., districts, cities, and counties) within Weifang as our study areas, with 2018–2021 used as the study period. Because Kuiwen, Weicheng, Fangzi, and Hanting are municipal districts, they were not included in this study. Economic, social, and environmental indicators for each study area were taken from the *Weifang City Statistical Yearbook* and *the Statistical Bulletin*. Interpolation was employed to replace missing data. According to statistics from *the China Phosphorus Compound Fertilizer Industry Association*, the domestic market share for Stanley's soil fertilizer products in 2022

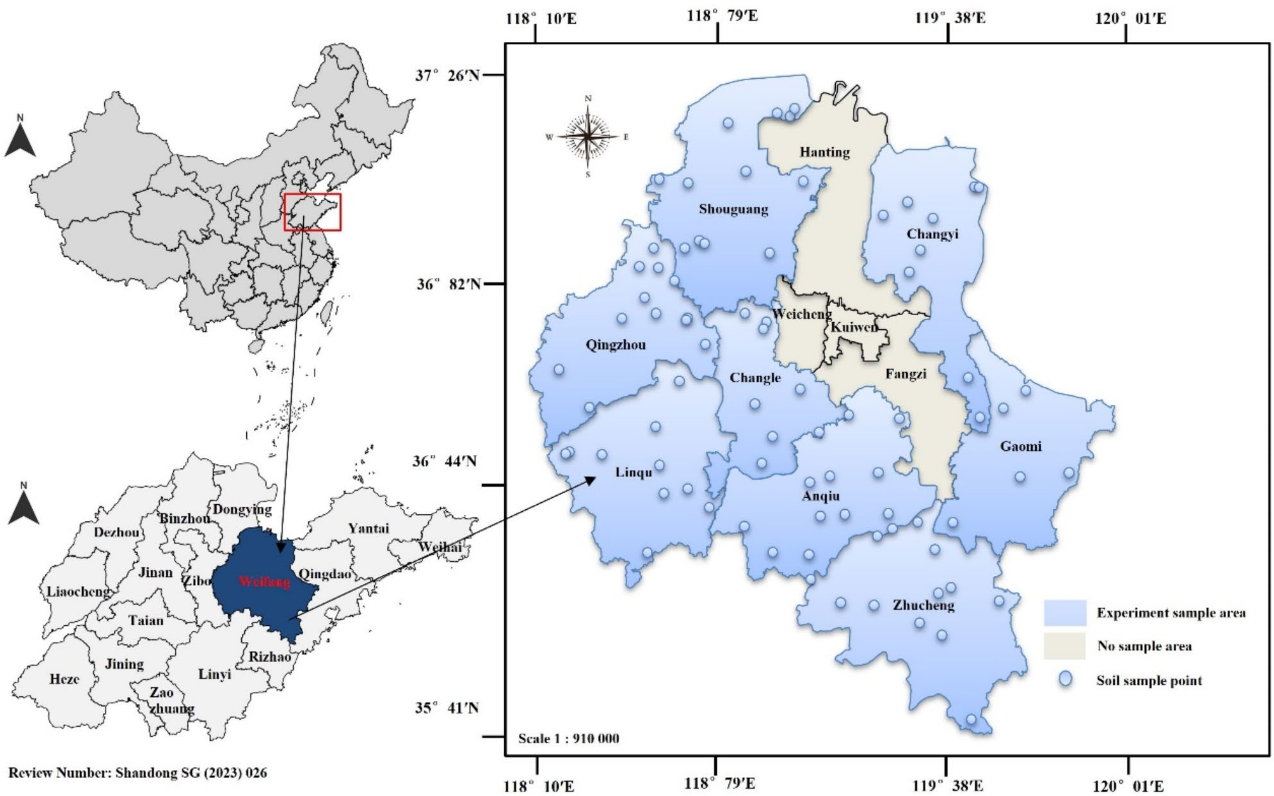

Fig. 2. Map of the study area.

Experimental area	Soil condition
Qingzhou	The low hills in the southern part of the region are dominated by brown soil, which has good aeration while retaining fertilizer and water, making it suitable for the forest and fruit industries. The middle and northern plains contain brown and fluvo-aquic soils, with good soil fertility and convenient irrigation conditions, making them important production areas for grains, vegetables, and other crops.
Zhucheng	The southern mountainous areas are dominated by brown soil, which can be used to grow specialty crops such as tea with careful soil and water conservation and fertilizer management. The brown and fluvo-aquic soils of the central and northern plains, with their high soil quality, are conducive to large-scale grain and vegetable production.
Shouguang	Highly fertile brown soil is found in some areas in the south, and it is suitable for growing vegetables, fruit trees, and other cash crops. Fluvo-aquic soil is present along rivers and in the central plains, with deep soil layers and a strong water and fertilizer retention capacity, providing an important base for a well-developed vegetable industry. The coastal saline soil in the northern coastal areas has a high salt content and requires a series of improvement measures before it can be used for agricultural production.
Anqiu	The southern mountainous areas are characterized by brown soil, with soil erosion a concern in some areas. Soil quality can be improved through measures such as afforestation. The central region is characterized by areas of brown soil and lime concretion black soil; the brown soils have fair soil fertility, while the lime concretion black soils need improvement to increase their productivity. Fluvo-aquic soil is widely distributed in the northern plains, which are an important area for agricultural cultivation.
Gaomi	The area is dominated by lime concretion black and fluvo-aquic soils, with high soil fertility, flat terrain, and good irrigation conditions, making it an important grain and cotton-producing area.
Changyi	Fluvo-aquic soil is found in the central and southern plains, where it is fertile and conducive to agricultural production. The northern coast has saline soil, and some progress has been made in its improvement and exploitation via projects such as saline-tolerant ecological restoration. Some low-lying areas have lime concretion black soil, which requires improvement in its structure to enhance its quality.
Linqu	The southern mountainous areas are mainly characterized by acidic brown loams, which are suitable for growing some acid-tolerant cash crops such as blueberries. The northern plains contain some brown and fluvo-aquic soils, and the soil quality is sufficient to grow a diverse range of crops.
Changle	The southern mountainous areas have brown loams with a moderate texture, good aeration and permeability, and a relatively high capacity for retaining fertilizer and water. The plains in the central and northern parts of the country are characterized by brown loams, which are suitable for growing a variety of crops such as wheat, corn, and cotton.

Table 1. Soil conditions within Weifang City.

was 4.4%, which is typical and representative. Therefore, we used Stanley's products as an example of the use of SHPs for some crops within the study areas (Table S2). Various other SHPs are also used in Weifang, but they are not listed here.

To ensure the authenticity and accuracy of the soil data, 5–10 sampling points were randomly selected at each research unit, with a sampling depth of 0–20 cm. The average value for these points was employed in the analysis. Data for the elemental soil content was provided by Stanley Agriculture Group Co., Ltd. and the Q In Soil Testing Lab.

Comprehensive benefit evaluation index for SHPs

We established a comprehensive evaluation index to assess the benefits of SHPs based on economic, social, and environmental indicators (Table 2). These indicators were selected in consideration of the soils in each study area with references to past research results[22,23], combined with relevant market data and product types provided by Stanley Agriculture Group Co., Ltd. and other scientific, rational, systematic, and operational considerations. The economic benefits included the sown area for food crops, per capita agricultural output, per capita disposable income in rural areas, and the per capita value added for the primary, secondary, and tertiary industries[24,25]. The social benefits were primarily related to the number of people employed in rural areas within the study area, the financial expenditure of urban and rural communities, and the number of people with a minimum subsistence guarantee in rural areas[26,27]. The environmental benefits were associated with the nitrogen, phosphorus, and potassium content of soil, the amount of fertilizer applied, and the amount of agricultural film used in the study area[28,29].

Research methods

Subjective and objective empowerment method

To avoid the subjectivity of weight assignment, we used the entropy value method as the objective means to determine the weight W of the SHPs indicators.

Step 1 For m study areas and n indicators, the original matrix $x = \{x_{ij}\} m \times n$ is constructed, wherex_{ij} denotes the value for indicator *j* in area *i*.

The available datasets were preprocessed to ensure different data sources could be compared. In particular, standardization methods were used according to the positive and negative attributes of the selected indicators[30]:

$$\text{Positive indicators : } x'_{ij} = x_{ij} - x_{\min}/x_{\max} - x_{\min} \tag{1}$$

$$\text{Negative indicators : } x'_{ij} = x_{\max} - x_{ij}/x_{\max} - x_{\min} \tag{2}$$

In Eq. (1) and Eq. (2), x'_{ij} is the standardized value of the sample data, x_{ij} is the original value of indicator *j* at study level *i*; $x\max$ and $x_{\min}$ represent the maximum and minimum values of indicator *j*, respectively.

Step 2 Information entropy *e* is calculated for each indicator *x* in the SHPs measurement system (Eq. 3):

Target level	Standardized level	Indicator level	Weight	Attribute
Comprehensive benefits of SHPs	Economic benefits	Area sown with food crops (hm^2)	0.2719	+
		Regional grain yields (kg/hm^2)	0.0667	+
		Agricultural output per capita (10,000/RMB)	0.1384	+
		Rural per capita disposable income (RMB)	0.1176	+
		Per capita added value for primary industry (10,000/RMB)	0.1300	+
		Per capita value added for secondary industry (10,000/RMB)	0.1316	+
		Per capita added value of tertiary industry (10,000/RMB)	0.1436	+
	Social benefits	Number of rural employees (10,000/person)	0.1414	+
		Per capita savings balance at the end of the year (10,000/RMB)	0.1280	+
		Expenditures on urban and rural communities (10,000/RMB)	0.4062	+
		Number of county general junior and senior high schools (1,000/person)	0.1324	+
		Number of hospital beds within the county	0.0803	+
		Number of people receiving a min-subsistence allowance in rural areas	0.1114	+
	Environmental benefits	Nitrate nitrogen (mg/kg)	0.2095	+
		Effective phosphorus (mg/kg)	0.1614	+
		Fast-acting potassium (mg/kg)	0.1743	+
		Organic matter (%)	0.1151	+
		pH	0.1443	-
		Agricultural fertilizer application (t)	0.0585	-
		Pesticide application (t)	0.0729	-
		Agricultural plastic film use (t)	0.0636	-

Table 2. Index system for evaluating the comprehensive benefits of SHPs based on economic, social, and environmental indicators.

$$e_j = -\frac{1}{\ln m}\sum_{i=1}^{m}\left[\left(x'_{ij}/\sum_{i=1}^{m}x'_{ij}\left(\ln\left(x'_{ij}/\sum_{i=1}^{m}x'_{ij}\right.\right.\right.\right] \quad (3)$$

Step 3 Weight *W* for each indicator *x* is calculated (Eq. 4):

$$W_j = (1 - e_j)/\sum_{i=1}^{n}(1 - e_j) \quad (4)$$

Step 4 The economic, social, and environmental benefit index scores *U* are calculated (Eq. 5):

$$U_{eco/soc/env} = \sum_{i=1}^{n}W_j x'_{ij} \quad (5)$$

Where U_{eco}, U_{soc} and U_{env} represent the economic, social, and environmental benefit scores, respectively. These scores are divided into five levels (Table 3). W_j is the corresponding indicator weight, and x'_{ij} is the standardized value of the indicator.

$$U_{com} = \alpha U_{eco} + \beta U_{soc} + \lambda U_{env} \quad (6)$$

In Eq. (6), U_{com} is the comprehensive benefits, and α, β and λ are the coefficients that are to be set, which indicate the degree of significance of the economic, social and environmental benefits of the SHPs. Considering that the above three need to be synergistically promoted and are nearly equally important, this paper will presume $\alpha = \beta = \lambda = 1/3$.

The comprehensive benefit scores for each study area and each year were divided into high, medium, and low benefit areas using the natural breakpoint method, which better demonstrates spatial and temporal evolution.

Coupling coordination degree model (CCDM)

The coupling coordination degree model (CCDM) is used to investigate how different subsystems influence each other, interact, and develop within a complex system[32]. This model allows the behavior and performance of system units to be studied from a holistic perspective by considering the interactions and feedback of individual subsystems. The CCDM is often employed to describe complex socio-economic systems, ecosystems, logistics systems, and multi-disciplinary problems[33]. By studying the coupling relationships and coordination modes between different subsystems, a system's operating laws can be understood, and its overall efficiency and resilience can be improved[34]. Equation (7) presents the calculation for the degree of coupling, while Eq. (8) is used to determine the degree of coordination:

$$C = \left[\frac{U_{env} \times U_{eco} \times U_{soc}}{\left[(U_{env} + U_{eco} + U_{soc})/3\right]^3}\right]^{\frac{1}{3}} \quad (7)$$

$$D = \sqrt{C \times U_{com}} \quad (8)$$

The degree of coupling is the lowest when *C = 0*, indicating that the subsystems under investigation are completely disordered, while *C = 1* represents a high degree of coupling between these subsystems. The present study referred to past research to classify the coordination level of the SHPs benefits system based on comprehensive benefit coupling coordination *D* (Table 4)[35]:

Score	Development level
0.00–0.09	Limitation
0.10–0.29	Low
0.30–0.49	Medium
0.50–0.69	High
0.70–0.99	Perfect

Table 3. Classification of the benefit scores. For the standardized level indicators, this study adopted the subjective assignment method, which assumes that the three subsets of economic, social, and environmental benefits of SHPs can promote and complement each other, with the weighting reflecting the importance of the three types of benefit[31]. We assumed that the three economic, social, and environmental subsystems were of equal importance, thus a weight coefficient of 1/3 was employed. Based on the comprehensive benefit evaluation index for SHPs, the economic, social, and environmental benefit scores for each study area were determined using Eq. (5). These scores were then used to calculate the comprehensive benefit score with Eq. (6):

Value range	Coordination level	Value range	Coordination level
0 < D ≤ 0.09	Extreme disorder (I)	0.49 < D ≤ 0.59	Barely Coordination (VI)
0.09 < D ≤ 0.19	Severe disorder (II)	0.59 < D ≤ 0.69	Primary coordination (VII)
0.19 < D ≤ 0.29	Moderate disorder (III)	0.69 < D ≤ 0.79	Intermediate coordination (VIII)
0.29 < D ≤ 0.39	Mild disorder (IV)	0.79 < D ≤ 0.89	Well coordination (IX)
0.39 < D ≤ 0.49	Near Disorder (V)	0.89 < D ≤ 0.10	Excellent coordination (X)

Table 4. Classification of the degree of coupling coordination.

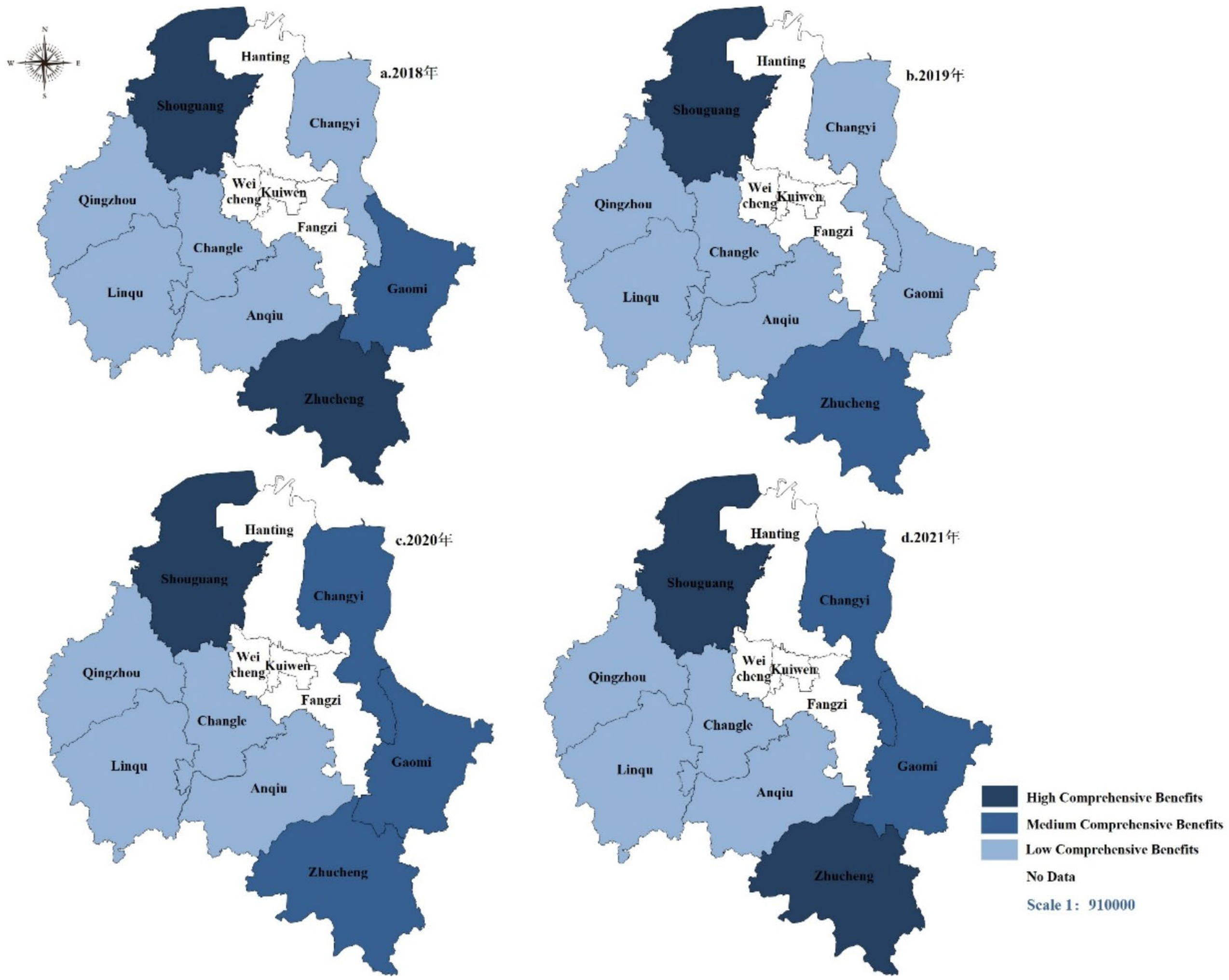

Fig. 3. Spatial pattern in the comprehensive benefit score for SHPs within Weifang by year.

Results
Comprehensive benefits
The comprehensive benefit scores for the SHPs in the study areas ranged from 0.271 to 0.563. Overall, the comprehensive benefits within Weifang were high in the northern and southern areas and low in the central regions (Fig. 3). Shouguang and Zhucheng had higher scores for comprehensive benefits than the other study areas, meaning that the effects produced by SHPs were significant there.

The comprehensive benefit score for SHPs within Weifang fluctuated from 2018 to 2021, though there was a general increase over time (Fig. 4a). This indicates that the use of SHPs increased the comprehensive benefits in this area, with a strong Matthew effect, i.e., the higher the comprehensive strength of the region, the higher the benefits obtained from the ecological restoration of soil. Based on "*2023 China's Top 100 County Economies Research*", Shouguang and Zhucheng were ranked 44th and 49th in China. Counties with stronger economies usually have more financial resources and funds to invest in environmental protection and soil remediation projects for the sustainable development of agriculture. Residents are also more likely to be aware

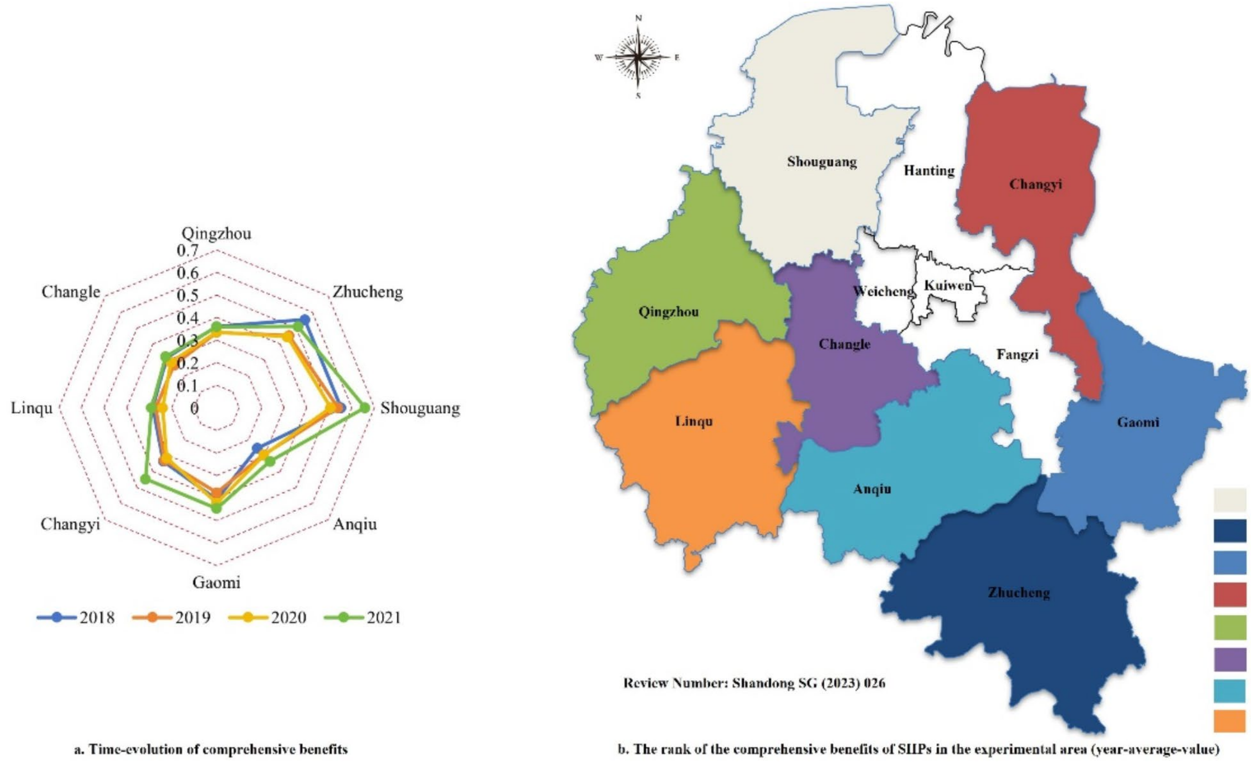

Fig. 4. Evaluation of the comprehensive benefit scores for SHPs.

of environmental problems with local soils, thus the use of SHPs is increased to promote the harmonious development of the economy, society, and environment.

Though the public health emergencies in 2019 and 2020 led to a decrease in the comprehensive benefits within some study areas[36], the overall impact appears to be controllable. Based on the average comprehensive benefit score across the entire study period, Shouguang was found to have the highest benefits of SHPs, followed by Zhucheng, Gaomi, Changyi, Qingzhou, Changle, Anqiu, and Linqu (Fig. 4b).

Economic benefits

As shown in Fig. 5, the mean economic benefit scores for the study areas ranged from 0.385 to 0.551, which was higher than the environmental and social benefit scores, with a general increase over time. Study areas in the northern (Shouguang) and eastern regions (Zhucheng, Changyi, and Gaomi) had higher and more stable scores. This situation is consistent with the assumption that farmers are economically orientated, with an expectation to maximize their benefits and promote agriculture as a high-value industry[37].

In particular, Shouguang is known as the “Hometown of Vegetables in China”. It emphasizes soil remediation and integrates soil ecological remediation into daily planting modes, leading to strong feedback[38]. For example, greenhouse cucumber growers in Gujiaqi Village, Luocheng Street, remediated their soil using platform technology, the occurrence of disease and pests in their greenhouses decreased, they reduced the use of fertilizers, and the taste of the cucumbers continuously improved, thus improving plant quality and the economic benefits.

In contrast, Linqu is a mountainous agricultural county with a high proportion of hilly areas, which limits the effectiveness of SHPs. The region’s agricultural infrastructure is also relatively underdeveloped, leading to a low economic benefit score.

Social benefits

The use of SHPs not only directly improved the quality of the soil environment in the study areas but also indirectly impacted the regional economy and society. The mean social benefit score ranged from 0.350 to 0.423 across the study areas and study period, with low volatility. The social benefit scores were higher in the north and south and lower in the middle of Weifang (Fig. 6), a distribution that was similar to that for economic benefits. The use of SHPs reduces soil pollutants, increases soil fertility, improves soil quality, and boosts crop yields while also reducing air and water pollution, improving soil ecology, and generating positive impacts for rural employment and social development.

It Is worth noting that the social benefit scores are low for Changle across the entire study period. *The Soil and Water Conservation Plan of Changle County (2016–2030)* reports that Changle soils are deficient in nutrients, the average organic matter content is 0.94%, and soil sloughing and erosion occur in some areas. Changle also has less arable land per capita and insufficient reserve resources for arable land, thus the social benefits of SHPs are less significant in this area.

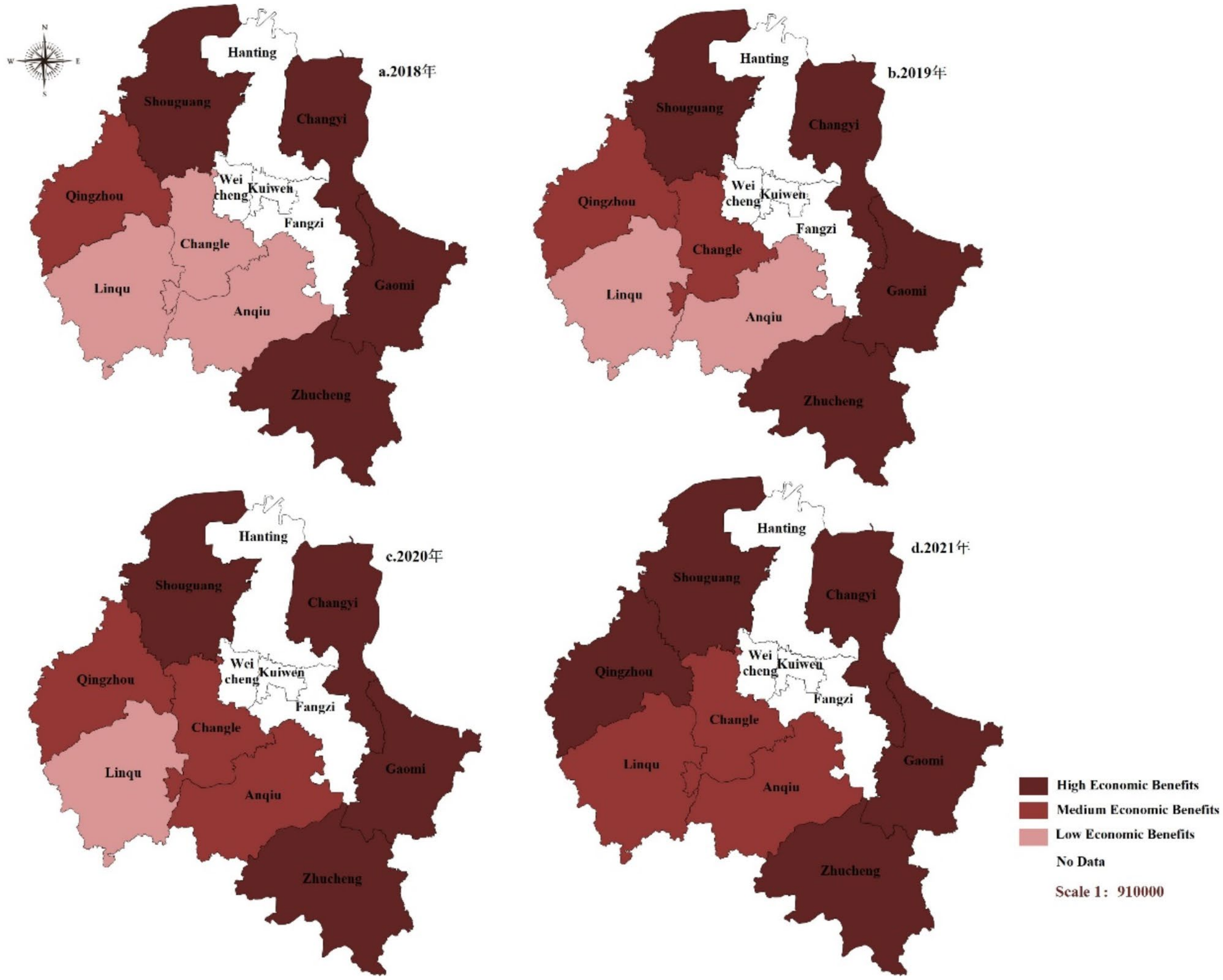

Fig. 5. Spatial pattern in the economic benefit score for SHPs in Weifang by year.

Environmental benefits

The mean environmental benefit score for SHPs across the sampling areas was low from 2018 to 2021, ranging from 0.278 to 0.359, with more obvious inter-regional differences. These scores were higher in the middle of Weifang and lower in the northern and southern regions (Fig. 7). The environmental benefits in Linqu were relatively stable, while those in Gaomi increased over the study period.

In Linqu, the government has strengthened environmental and ecological protection, promoted agriculture in mountainous areas, introduced three significant pollution prevention and control actions. Gaomi implements the requirements of the "*Technical Report on Classification of Arable Land Soil Environmental Quality Categories in Gaomi*." It continues to promote the reduction of fertilizers and pesticides to improve the quality of arable land. However, other types of environmental benefit still need to be improved, both at a macro level to strengthen soil regulation and at a micro level to implement SHPs.

Degree of coupling coordination

Changes over time and Spatial divergence

Each study area was classified by calculating the degree of coupling coordination between the economic, social, and environmental benefits and combining the results with the classification criteria in Table 3. In terms of changes over the study period, the coupling coordination in each area tended to trend upward (Table 5), though it did decline in some regions in 2020 because of the impact of public health emergencies and other factors. However, each area crossed into the category of the coordination grade in 2021. There is one area each with excellent, well, intermediate, and primary coordination grades, but the remaining four regions are all barely coordinated, which shows that the level of coordination and coupling of each subsystem in some areas still needs further improvement.

Qingzhou's coupling coordination changed from primary coordination to barely coordinated, while Zhucheng fluctuated between intermediate and well coordination over the study period. Shouguang maintained a high level of coupled coordination throughout the study period, moving from well coordination in 2018 to excellent coordination in 2021. Anqiu's coupling coordination degree was on the verge of dysfunction to

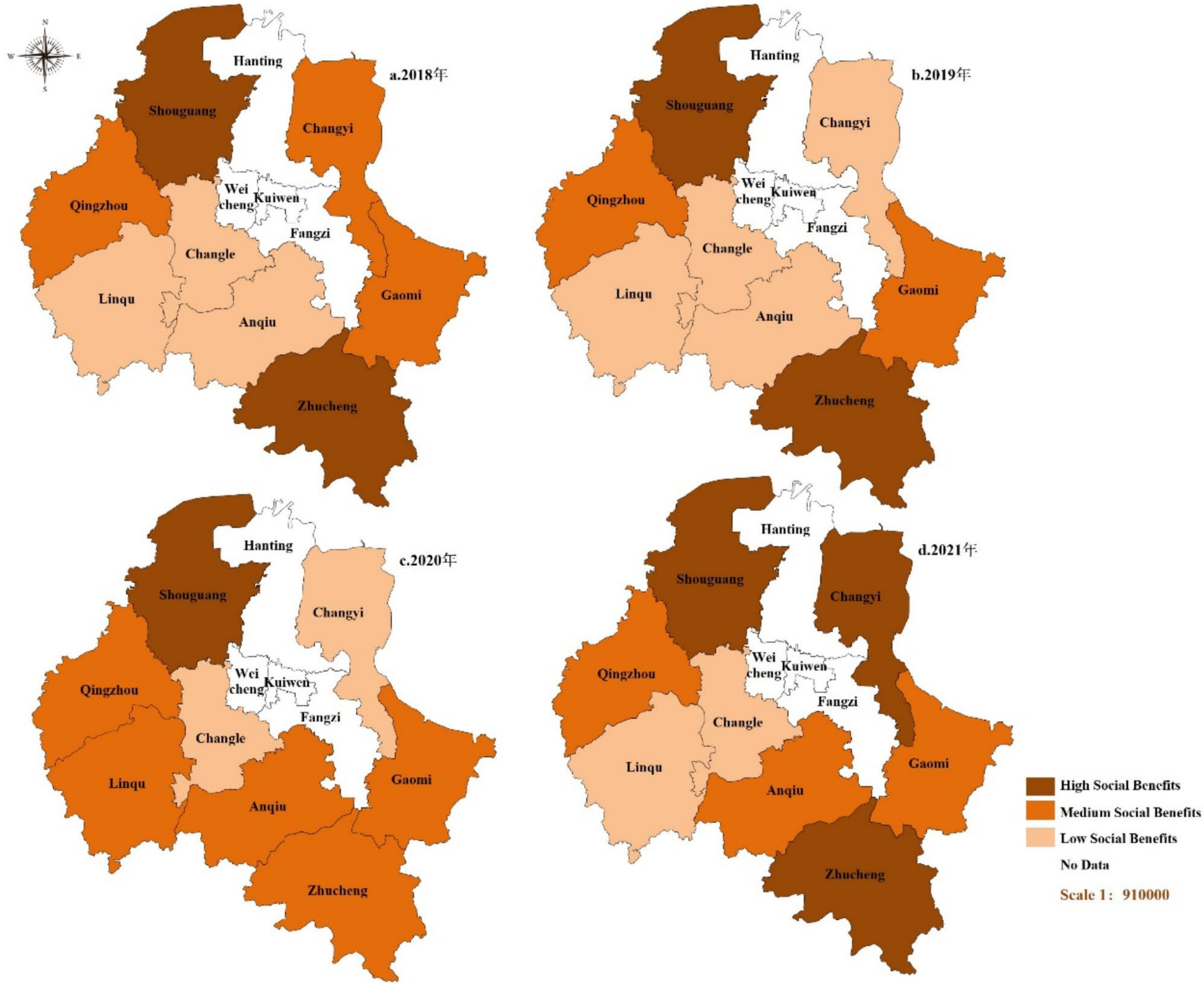

Fig. 6. Spatial pattern in the social benefit score for SHPs in Weifang by year.

barely coordinated, before crossing into the coordinated level. Gaomi changed from primary coordination to intermediate coordination, while Changyi rose from barely coordinated to primary coordinated and Linqu fluctuated between dysfunction and coordination. Finally, Changle's coupling coordination was more stable, but it remained at the barely coordinated level.

In terms of the spatial distribution (Fig. 8), the lowest degree of coupling coordination occurred in the middle of Weifang, with a higher degree of coupling coordination observed in the northern (Shouguang) and the southeastern areas (Gaomi and Zhucheng). This was likely due to the high level of agricultural economic development in these areas, which has created a complete industrial chain from planting and processing to sales. Local governments and companies attach great importance to research and development and the application of agricultural science and technology and have continuously invested in vegetable cultivation technology, greenhouse facility construction, and agricultural product quality testing, thus promoting agricultural modernization.

The coupling coordination in the central areas (e.g., Linqu and Anqiu) still needs to be improved because it sits on the boundary between dysfunctionality and barely coordinated. These areas may be limited by land resources and agricultural technology, reducing agricultural production and resource utilization and making it difficult to effectively coordinate the agricultural economy, society, and environment. In addition, the agricultural products from the central areas may not fully meet market demands, negatively impacting sales of agricultural products and agricultural output, resulting in a lower degree of coupling coordination.

Limitations to the coupling coordination degree

Based on 2021 data, the coupling coordination relationships in the study areas were classified into four categories: complete lag, environmental benefit lag, economic–social benefit lag, and environmental–social benefit lag. The aim of this was to identify constraints and thus increase the coupling coordination for the benefits of using SHPs within study areas[39]. As shown in Table 6, there was one area with an environmental benefit lag for SHPs, four

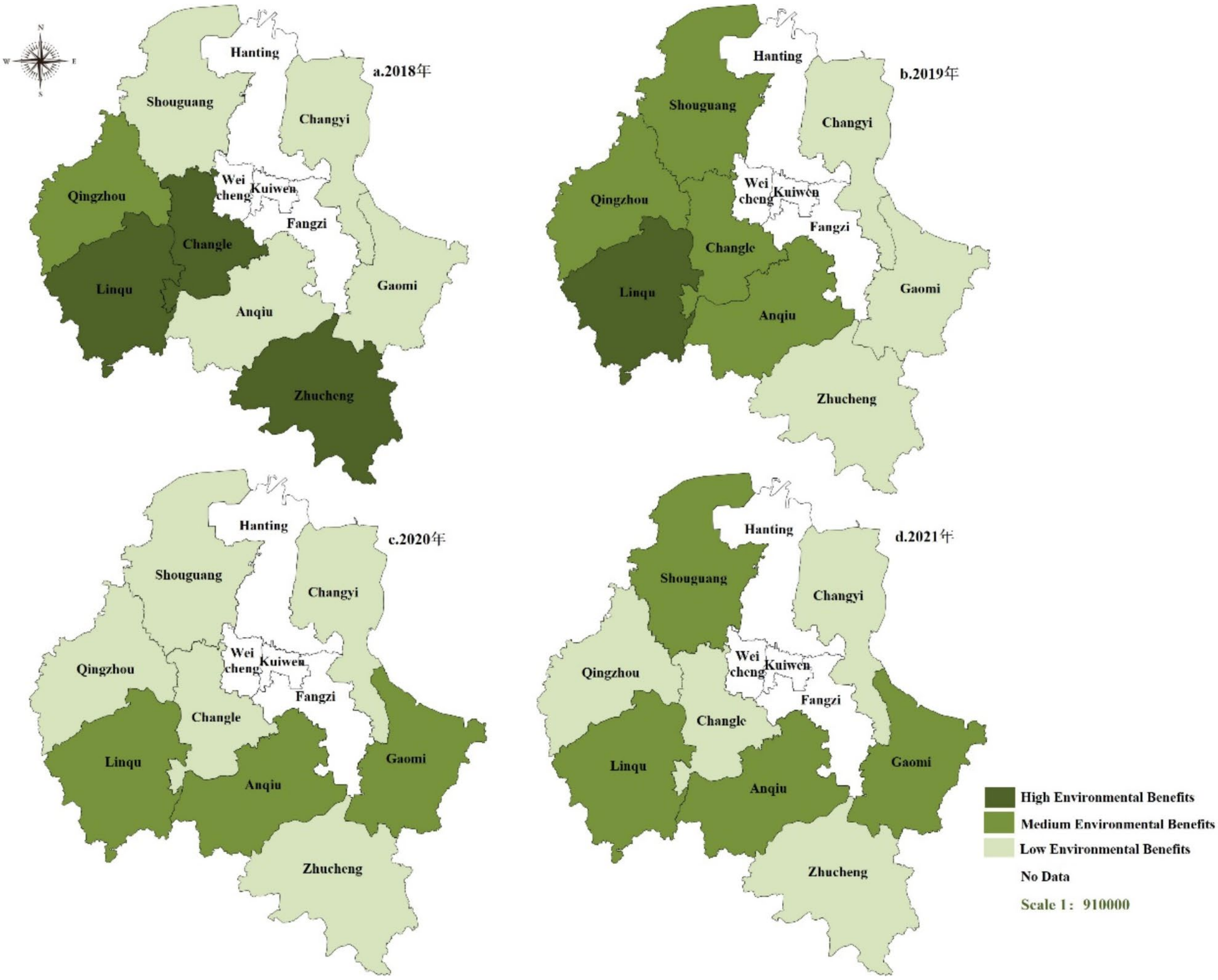

Fig. 7. Spatial pattern in the environmental benefit score for SHPs in Weifang by year.

	2018		2019		2020		2021	
Area	D	level	D	level	D	level	D	level
Qingzhou	0.6153	VII	0.5784	VI	0.5798	VI	0.5984	VI
Zhucheng	0.8754	IX	0.7220	VIII	0.7012	VIII	0.8015	IX
Shouguang	0.8466	IX	0.8397	IX	0.7360	VIII	0.9682	X
Anqiu	0.4557	V	0.5123	VI	0.5203	VI	0.5799	VI
Gaomi	0.6612	VII	0.6264	VII	0.6958	VIII	0.7123	VIII
Changyi	0.5562	VI	0.5437	VI	0.5054	VI	0.6891	VII
Linqu	0.4049	V	0.4076	V	0.4112	V	0.5007	VI
Changle	0.5353	VI	0.4711	VI	0.5045	VI	0.5432	VI

Table 5. Classification of coupled coordination level of economic, social, and environmental benefits of SHPs.

areas where the coupling coordination relationship was out of order because of the joint influence of social and other subsystems, and two areas where the economic, social, and environmental benefits were all lagging.

Zhucheng was found to exhibit a lag in terms of environmental benefits. According to Zhucheng Agricultural and Rural Bureau, its regional soils are mainly acidic, primarily due to the overuse of chemical fertilizers. The organic matter content of the soil is also moderately low, so soil ecological restoration needs to be strengthened. Soil environmental benefits are related to various factors, such as soil texture, organic matter content, acidity, alkalinity, and water levels. SHPs-based amendment may thus improve soil health.

Qingzhou and Changle both exhibited a complete lag. The soil of Qingzhou has significant geographical differences, and it is dominated by brown and fluvo-aquic soil[40]. The moist soil in the northern low-lying

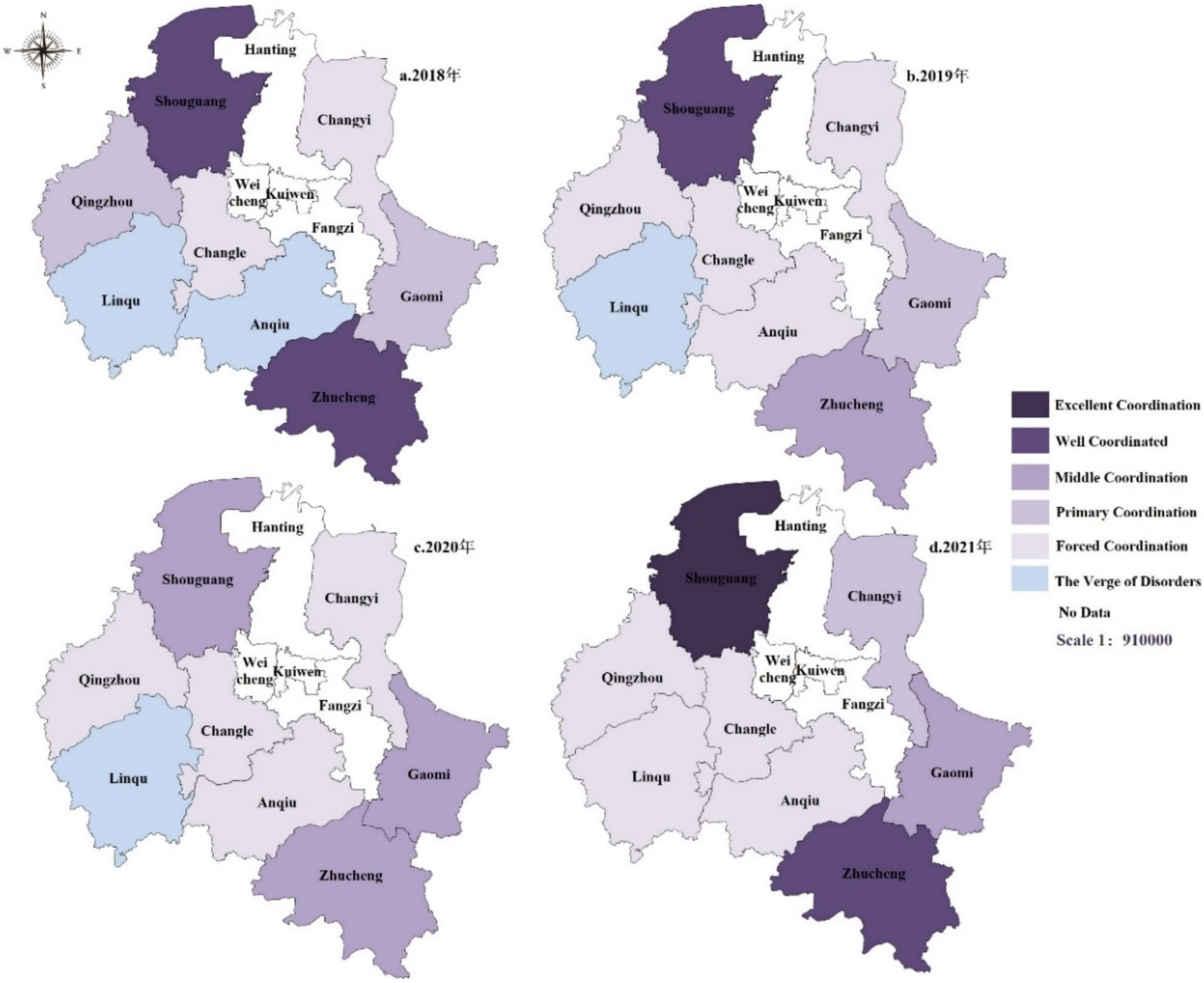

Fig. 8. Changes in the spatial distribution of coupling coordination of SHPs benefits.

Classification	Classification basis	Study areas in 2021
Complete lag	$U_{env} < \overline{U_{env}}, U_{eco} < \overline{U_{eco}}, U_{soc} < \overline{U_{soc}}$	Qingzhou
Environmental benefit lag	$U_{env} < \overline{U_{env}}, U_{eco} > \overline{U_{eco}}, U_{soc} > \overline{U_{soc}}$	Zhucheng
-	$U_{env} > \overline{U_{env}}, U_{eco} > \overline{U_{eco}}, U_{soc} > \overline{U_{soc}}$	Shouguang
Economic-social benefit lag	$U_{env} > \overline{U_{env}}, U_{eco} < \overline{U_{eco}}, U_{soc} < \overline{U_{soc}}$	Anqiu
Environmental-social benefit lag	$U_{env} < \overline{U_{env}}, U_{eco} > \overline{U_{eco}}, U_{soc} < \overline{U_{soc}}$	Gaomi
Environmental-social benefit lag	$U_{env} < \overline{U_{env}}, U_{eco} > \overline{U_{eco}}, U_{soc} < \overline{U_{soc}}$	Changyi
Economic-social benefit lag	$U_{env} > \overline{U_{env}}, U_{eco} < \overline{U_{eco}}, U_{soc} < \overline{U_{soc}}$	Linqu
Complete lag	$U_{env} < \overline{U_{env}}, U_{eco} < \overline{U_{eco}}, U_{soc} < \overline{U_{soc}}$	Changle

Table 6. Classification of lag types in coupled coordination analysis for SHPs benefits within the study areas. Note: U_{env}, U_{eco} and U_{soc}indicate the environmental, economic and social benefits of soil health products for the region in 2021; $\overline{U_{env}}$, $\overline{U_{eco}}$ and $\overline{U_{soc}}$ indicate the mean values of the environmental, economic and social benefits of SHPs for the corresponding regional year, respectively.

areas leads to uneven coordination between water and temperature, with water and fertilizer loss emerging as significant problems, hindering agricultural development. Most areas in Changle have weak acidic or alkaline soils with low organic matter, nitrogen, and phosphorus content, restricting soil recovery. Some farmers in Changle also need to improve their awareness and acceptance of SHPs because of the influence of traditional agricultural cultivation habits and market perceptions. The effects of SHPs may thus take a longer time to emerge

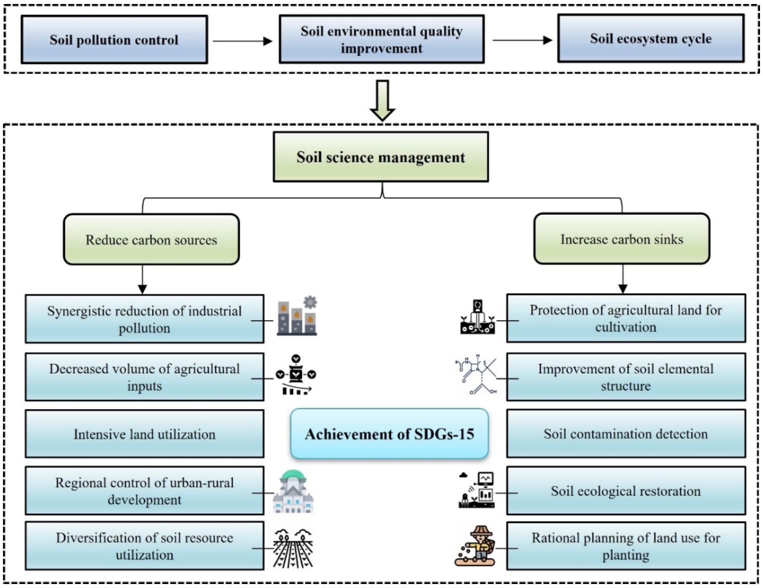

Fig. 9. Basis for Weifang's science of soil management.

in this area, meaning that, if the monitoring and evaluation cycle is too short, the long-term benefits of the products may not be adequately reflected in the analysis.

Anqiu and Linqu exhibited lagging economic–social benefits. These areas have certain advantages for agricultural development, including flat terrain, the Mihe River, and sufficient water sources, but the structure of the agricultural industry is relatively single, the development of modern agricultural mechanization and scaling is relatively slow[41], and the level of agriculture and soil protection technology is low. There are also fewer workers engaged in agricultural cultivation. Although the environmental benefits of these regions have been improved with SHPs, the economic and social benefits remain relatively weak.

Gaomi and Changyi exhibited lagging environmental–social benefits. According to the results of past studies, administrators in Gaomi applied 2011–2018 soil sanitation survey data and randomized some administrative villages as monitoring points to understand regional soil contamination with lead and cadmium[42]. The average cadmium levels exceeded *Soil Environmental Quality Standards (GB15618-1995)*, though the soil was not significantly contaminated by lead. Gaomi and Changyi may also have an imbalance in agricultural economic development, and some areas or industries still need to pay attention to the protection of soil quality and the ecological environment, which leads to lower environmental and social benefits.

Discussion

Effects of soil protection in Weifang City

The results of the present study showed that the economic, social, and environmental benefits derived from SHPs should receive significant attention in Weifang. The coupling coordination relationship tends to be close to dysfunction, and there are some notable differences between regions. Currently, Weifang actively implements soil remediation projects (Fig. 9 and Fig. S1) and chemical fertilizer, pesticide reduction, and efficiency programs[43]. It strongly promotes comprehensive soil testing, water and fertilizer integration, green pest and disease prevention, and the promotion of advanced technology so that damaged land can be remediated to produce high-quality products.

Based on these findings, Shouguang was ranked highest for all measures. There are a few reasons for this. First, Shouguang is unique in its geography and climate, which is suitable for the growth of plants and the production of high-quality agricultural products, which leads to stable agricultural output[44]. Through the implementation of agricultural modernization initiatives and innovative scientific and technological measures, the efficiency of Shouguang's agricultural production has also been enhanced[45]. Second, this area prioritizes soil protection and restoration, thus protecting the agricultural environment and improving its ecological benefits. With a series of policy provisions in place to support agricultural development, including financial support and technical guidance, agricultural production and farming incomes have increased. Third, the Shouguang government focuses on educating and training farmers to raise their quality and skill levels, enabling them to better adapt to the needs of modern agricultural production. These actions have promoted the coordination of the economic, social, and environmental benefits of SHPs.

Promotion of coupling coordination

For the areas experiencing a complete lag (Qingzhou and Changle), the government should continuously increase investment in research and development and provide guidelines and training for the use of the SHPs, including how to apply the products to the soil, the dosage required, and optimal application time. The construction of a soil environment monitoring system would also allow changes in soil quality to be tracked and provide a scientific basis for the rational use of SHPs. In conjunction with local ecological protection planning, suitable SHPs for local ecological conditions should be promoted, and the positive interaction between the ecological environment and industrial development should be facilitated. This will improve the popularity of SHPs in regional agricultural systems, maximize the economic benefits, and promote the enhancement of environmental and social benefits.

In Zhucheng, which has lagging environmental benefits, eco-agriculture needs to be promoted to reduce the chemical pollution of the soil and protect the soil ecosystem. Green planting techniques (such as plant mulching, irrigation, and water conservation) and soil health management could increase the soil nutrient content, reduce the impact of soil pollution on the environment, enhance the effectiveness of SHPs in regions with lagging environmental benefits, contribute to the improvement of the soil and the ecological environment, and realize the goal of sustainable agricultural development. The government should also establish SHPs promotion service network to provide farmers and agribusinesses with one-stop services such as technical advice and product distribution.

For the areas with lagging economic and social benefits (Anqiu and Linqu), local governments should provide planting organizations with subsidies for the purchase and production of SHPs to boost crop yields and quality. Anqiu and Linqu can also extend the industrial chain for the processing of agricultural products, more fully process agricultural products, and improve their added value and market competitiveness. Demonstration projects for the use of SHPs can also be set up, and agricultural cooperatives can be established to implement an intensive management model for the joint purchase of products, sharing resources, and enhancing economic benefits. Thus, training courses on SHPs need to be conducted to improve the professional knowledge and skills of farmers, enhance the quality of agriculture, and improve social benefits. In the future, soil research in these areas, targeted improvement measures, and soil health restoration and cultivation should be pursued, and agriculture should be improved according to local conditions to maximize the comprehensive benefits of using SHPs.

For areas with lagging environmental and social benefits (Gaomi and Changyi), agricultural and technical departments should scientifically establish soil health management plans to protect the farming functions of farmland soils and reduce the over-exploitation and pollution of soil resources. Soil health protection campaigns and education activities should be used to raise the awareness of the public and farmers regarding soil environmental protection, advance scientific cultivation methods, and attract highly qualified rural returnees to soil science management. Environmental and market regulators should also strengthen the environmental supervision of the SHPs production process to ensure that companies strictly comply with environmental protection standards and reduce pollutant emissions. Carrying out soil ecological remediation projects, combined with the application of SHPs, will improve the quality of contaminated soil and restore soil ecological functions.

Research limitations

This paper focuses on the evaluation of the benefits of SHPs in Weifang City, revealing the evolution of each subsystem and their coupling coordination relationships and provides a reference for regional soil ecological management. Nonetheless, this study has some limitations that should be considered. First, the indicator system needs to be developed further because some environmental indicators were not included, such as soil carbon sequestration, water retention capacity, and soil environmental carrying capacity, while the economic and social benefit indicators used were relatively broad in their scale. The research was also conducted at the county level, and the soil samples were selected from a broader range of soil samples. However, there are significant differences in the soil content between regions, which may have influenced the study results. Therefore, the indicator system should be refined using a research unit that better demonstrates the benefits of SHPs and enhances the scientific foundation of the results. In addition, the study period was relatively short, meaning that the long-term benefits of SHPs were unlikely to be captured. We thus plan to strengthen cooperation with soil testing institutions in follow-up research.

Conclusion

Soil science management is the basis for sustainable agricultural development. This paper evaluated the comprehensive benefits of SHPs and the coupled and coordinated relationships of the benefit subsystems. The study results will guide planting organizations in choosing appropriate products and methods, reducing the negative impacts of fertilizer and pesticide application, lowering the risk of contamination for soil and water bodies, and increasing the benefits and ecological value of agricultural production. The main findings are summarized below:

(1) The comprehensive benefit score for SHPs in Weifang City exhibited a gradual upward trend over time. Shouguang City had the highest comprehensive benefit score, with a strong Matthew effect.
(2) The economic benefits were higher in the northern and eastern regions of Weifang and lower in the south-western regions. The social benefits only varied weakly over time, while the environmental benefits of SHPs in Weifang were higher in the central regions and lower in the north and south.
(3) The coupling coordination level constantly fluctuated but generally improved over time. The overall level of each subsystem skirted the boundary between coordination and disorder, with some of the study areas in a state of disorder. The spatial differences were more pronounced.
(4) Multiple factors affected the coupling coordination relationships for SHPs within the study areas. Especially, Qingzhou and Changle demonstrated a complete lag of benefits, which may be related to their current local natural environment and economic development.

Data availability
The datasets used in the present study (e.g., soil elemental data) are not publicly available because they were derived from a field experiment, but they are available from the corresponding author upon reasonable request.

Received: 2 October 2024; Accepted: 25 March 2025
Published online: 01 April 2025

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Acknowledgements
This study was supported in part by grants from the key research and development program (Science and technology demonstration project) of Shandong Province: Intelligent soil health product configuration system construction and technology integration demonstration (2022SFGC0303).

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Yuhu Cui: Data curation, Formal analysis, Writing – original draft. Jie Zhang: Investigation, Resources, Data curation. Xueshi Xie: Project administration. Li Zhou & Wentao Wu: Investigation, Resources. Lin Yang: Writing – review & editing, Project administration, Validation. All authors reviewed the manuscript.

Funding
This study was supported in part by grants from the key research and development program (Science and technology demonstration project) of Shandong Province: Intelligent soil health product configuration system construction and technology integration demonstration (2022SFGC0303).

Declarations

Competing interests
The authors declare no competing interests.

Additional information
Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-025-96022-6.

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