

RESEARCH ON THE AGRICULTURAL RESOURCES COUPLING COORDINATION DEGREE AND ITS INFLUENCING FACTORS IN THE LOESS PLATEAU OF CHINA FROM THE PERSPECTIVE OF THE "FOOD-ENERGY-WATER NEXUS"

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Abstract. Quantitatively measuring the stock status of resources in the Loess Plateau of China and revealing resource associations and influencing factors is urgent since it is the scientific basis of realizing regional sustainable development. This paper first calculates the stocks of food, agricultural energy, and agricultural water resources from the perspective of supply and demand of resources. Then the coupled coordination model is used to study the relationship between resources, and the geodetector was applied to reveal their driving factors. Finally, the cross-sectional threshold model is used to analyze the relationship between economic growth and resource decoupling and coordination. The research shows that: (1) The key problem hindering the sustainable development of the Loess Plateau of China from 2000 to 2020 is the imbalance of resource supply and demand. (2) From 2000 to 2020, most cities in the Loess Plateau of China were in a state of coordinated development. (3) The total power of agricultural machinery, the GDP per capita, and the resident population are the dominant factors affecting the coupling and coordination of resources in the Loess Plateau of China. (4) Nonlinear relationship was observed between economic growth and resource coupling coordination degree in the Loess Plateau of China.

Keywords: *agricultural resources nexus, spatio-temporal heterogeneity, synergies and trade-offs, threshold effect, regional sustainable development*

Introduction

Food, energy and water resources are the basic resources for regional sustainable development (Nilsson et al., 2016). With the rapid improvement of economic level, continuous progress of urban construction and substantial increase of population, resources are faced with the problem of increasing demand and limited supply, which brings severe challenges to the security of resource systems. It is estimated that by 2030, human demand for food, energy and water resources will increase by 35%, 50% and 40% respectively (Zhang et al., 2019). For example, the COVID-19 epidemic has restricted the flow of resources, and the importance of regional self-sufficiency has become more and more obvious. With economic security, food security, ecological security and energy security as the core, the study of high-quality development of agriculture and rural areas has received attention (Zhang et al., 2021). The "Food-Energy-Water Nexus" (FEW Nexus) study is based on resource security issues. For instance, under rapid urbanization, the pattern of food, energy and water resources distribution in our country is discussed and also possibilities for modifications are

analysed (Zhang et al., 2018); climate change and labor factor input are usually the main driving factors for change (Han et al., 2019); and the uncertainty of supply and demand of food, energy and water resources intensifies the pressure on the society ecosystem (Khan et al., 2009; Zand et al., 2019).

There are complex synergies and trade-offs among food, energy and water resources, which provide a crucial foundation for regional sustainable development (Nilsson et al., 2016). In 2011, the "Global Risks Report" identified the "Food-Energy-Water Nexus" as a risky issue affecting regional development. The spatial and temporal distribution and influencing factors of the "Food-Energy-Water Nexus" have attracted much attention from the academic community (Feng et al., 2020; Zhang et al., 2023). Especially in the context of rapid economic development and urbanization, significant changes have taken place in the spatial distribution characteristics of food, energy and water resources, supply and demand structure, and environmental quality, which aggravate the pressure among food, energy and water resources in China and restrict the sustainable development of our country (Zhang et al., 2019). The "Food-Energy-Water Nexus" is affected by many factors such as climate change, economy and society, so it has become an urgent scientific problem to explore the existing correlation in the study of regional sustainable development.

In order to reveal the complex relationship of synergies and trade-offs among multiple resource systems, geographically weighted regression model (Yu et al., 2022), Gedetector (Zhang et al., 2022a; Lv et al., 2022), coupling coordination degree model (Dong et al., 2023a), system dynamics model (Wen et al., 2022), input-output model (Zhang et al., 2022b), life cycle evaluation (Al-Ansari et al., 2015) and other models with mature application are frequently used to carry out quantitative research. In addition, the correlation pressure index model (Zhu et al., 2021) is specially designed for the analysis of the "Food-Energy-Water Nexus", and the efficiency of the "Food-Energy-Water Nexus" is evaluated based on the ME-DEA model (Han et al., 2019). Omolola's research results show that in the case of resource exhaustion, sustainable management of natural resources can improve food security (Ogbolumani and Nwulu, 2021), and reasonable management of natural resources can provide institutional guarantee for rural revitalization strategy (Deng et al., 2022).

The security of food, energy, and water resources constitutes a critically important research issue. Insecurity of food, energy and water resources has seriously threatened the health of ecosystem and human well-being (Biggs et al., 2015), and the scarcity of food, energy and water resources urgently needs to be studied. Existing studies focus on the dynamic changes of resources from the perspectives of supply and demand to reflect the situation of regional resources. Taking the Yangtze River Delta as a case study and analyzed the dynamic changes of the ecosystem from the perspectives of supply and demand, providing support for the formulation of effective resource management policies (Xu et al., 2020). Qualitatively analyzing the relationship between commodities and services provided by multifunctional agriculture and social demand, and the research result was mismatch between supply and demand (Zasada et al., 2011). Assessing the impact of food security on water, energy, land and CO₂ emissions shows that food production uses more water, energy and land (Lee et al., 2018).

The study of "Food-Energy-Water Nexus" has become an important issue of sustainable development, and the coupling coordination degree model is relatively mature as an evaluation method of "Food-Energy-Water Nexus". The coupling coordination degree model is a mature method to evaluate the grain-energy-water

correlation. Accurately elucidating the coupling coordination relationship between urbanization and air quality is an important prerequisite for improving their coordinated development and realizing new urbanization (Dong et al., 2023b). The water footprint sustainability assessment used a comprehensive evaluation method, and the coupling coordination degree model was applied to analyze the coupling coordination of the system water footprint sustainability (Jiang et al., 2022). Quantitative analysis of the "Food-Energy-Water Nexus" is helpful to improve food, energy and water security, reduce the tradeoff between resources, and promote the coordinated development of resources. There are many researches on the threshold effect of factors influencing coupling coordination degree. Scholars analyze the threshold effect of factors influencing coupling coordination degree from different perspectives. The coupling coordination degree and threshold model was applied to study the coupling coordination relationship between new urbanization and industrial structure upgrading in provinces, regions and cities in China, as well as the threshold effect of new urbanization on industrial structure upgrading (Fang et al., 2020). Analyzing the coupling and coordination relationship between digital economy and environmental quality, and analyzed the threshold effect of digital economy on environmental quality under the influence of urbanization, population density and economic development threshold variables (Li et al., 2021).

Previous studies have extensively explored the issues of escalating resource demand coupled with supply constraints (Feriha et al., 2015; Ogbolumani et al., 2021). Within the framework of the "Food-Energy-Water Nexus", methodologies for assessing resource coupling coordination degree are relatively mature, providing a solid methodological foundation for this study. The determinants of resource coupling coordination degrees encompass series of variables, namely climate change, educational attainment, economic development, technological level, financial support, industrial structure, consumption level, population density, and so forth. These factors collectively serve as a research basis for identifying the influential factors of coupling coordination degree in this study. Nevertheless, the existing research deficiencies are primarily reflected in the lack of in-depth exploration of analyses into the interrelationships among food, agricultural energy and agricultural water resources from the perspective of resource supply and demand, as well as inadequate research on their spatiotemporal heterogeneity.

The Loess Plateau of China is an important part of ecological protection and high-quality development of the Yellow River Basin. The fragile ecological environment, climate change and human activities have further aggravated the contradiction between the social and ecological system, and there are still practical issues with sustainable development of the region. Meanwhile, the surge in population and the advancements in agriculture development necessitate the substantial consumption of food, energy, and water resources, leading to a progressively prominent contradiction between the dwindling water resources and the increasing demands for energy and food. This phenomenon poses a severe challenge to the security of agricultural resource systems in the Loess Plateau region, further constraining economic development and social stability in this area. Under such circumstances, merely optimizing a single resource cannot adequately address the complex issues confronting the Loess Plateau region. Therefore, it is essential to prioritize the coordinated development of food, energy, and water resources to guarantee the resource security for agricultural development in the Loess Plateau region.

Accordingly, this study selected cities in the Loess Plateau as the research object, measured the supply and demand status of food, agricultural energy and agricultural water resources in 2000, 2005, 2010, 2015 and 2020, used the coupling coordination degree model to study the spatio-temporal differentiation characteristics of the "Food-Energy-Water Nexus", and explored its driving factors based on the geographical detector method. The threshold model is used to study the nonlinear relationship between economic development and resource coupling degree. This study is based on the perspective of the coupling and correlation of the "Food-Energy-Water Nexus". It systematically analyzes the coupling coordination degree of agricultural resources in the Loess Plateau region and its key influencing factors. The research results not only provide an innovative research paradigm for regional sustainable development and high-quality development, but also contribute to solving the current contradiction between economic growth and the efficient utilization of agricultural resources in the Loess Plateau region. It holds significant theoretical value and practical guiding significance for promoting the region to achieve the goals of resource-intensive and environmentally friendly high-quality development.

Materials and research methods

Study area and data source

The Loess Plateau of China includes 44 cities in Shanxi, Shaanxi, Gansu, Qinghai, Ningxia and Henan provinces and Inner Mongolia Autonomous Region which are located in the range of $33^{\circ}41'N$ - $41^{\circ}16'N$, $100^{\circ}54'E$ - $114^{\circ}33'E$ (Figure 1). Due to loose soil quality, serious soil erosion, resulting in water shortage, agricultural energy supply shortage, agricultural production conditions backward, low and unstable food production, causing tremendous pressure on agricultural development.

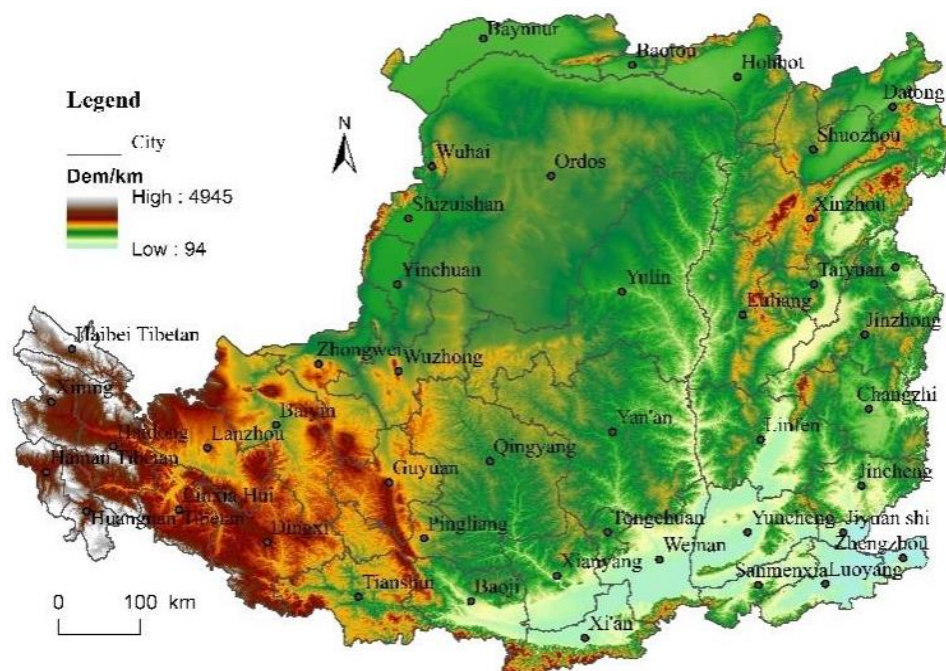


Figure 1. Location of the study area

This study examines the synergies and trade-offs among food, agricultural energy and agricultural water resources in the Loess Plateau of China. The index data mainly come from "China City Statistical Yearbook", "China Energy Statistical Yearbook", "China Regional Statistical Yearbook", provincial statistical yearbook, provincial water resources bulletin, municipal statistical yearbook and national economic and social development bulletin. The study period is 2000, 2005, 2010, 2015 and 2020. In addition, DEM data (resolution 1km×1km) are obtained from Data Center for Resources and Environmental Sciences, CAS (<http://www.resdc.cn/>) (Table 1).

Table 1. Data source

Data	Unit	Data source
Food production	10 ⁴ t	China City Statistical Yearbook
Per capita grain consumption	10 ⁴ t	China Provincial Statistical Yearbook
Urban permanent population	10 ⁴ people	China City Statistical Yearbook
Rural permanent population	10 ⁴ people	China City Statistical Yearbook
Total power of agricultural machinery	10 ⁴ kw	China City Statistical Yearbook
Final energy consumption in agriculture, forestry, animal husbandry and fishery sectors	10 ⁴ tce	China Energy Statistical Yearbook
Gross output value of the primary industry	10 ⁸ yuan	China City Statistical Yearbook
Agricultural water consumption	10 ⁸ m ³	China Provincial Water Resources Bulletin
Total water resources	10 ⁸ m ³	China Provincial Water Resources Bulletin
Effective irrigation area	10 ³ hm ²	China City Statistical Yearbook
Administrative area	10 ³ hm ²	China City Statistical Yearbook
DEM	1 km×1 km	Data Center for Resources and Environmental Sciences, CAS

Quantitative calculation of food, agricultural energy and agricultural water resources from the perspective of resource supply and demand

Based on the practical background of resource security, which restricts regional sustainable development, this paper discusses some practical problems such as uneven distribution of resource space, shortage of water resources, food security, contradiction between resource utilization and economic development in the Loess Plateau of China. The necessity of regional coordinated development in the loess Plateau region under the constraint of resources is put forward. The research is carried out according to the logical thinking of quantitative calculation of food, agricultural energy and agricultural water resources, identification of influencing factors and analysis of threshold effect of influencing factors. Firstly, the status quo of agricultural resources and the coupling coordination degree of agricultural resources in the Loess Plateau region are measured, then the influencing factors of the coupling coordination degree of agricultural resources are identified, and the threshold effects of the influencing factors are analyzed. The relevant methodologies are presented below (Figure 2).

Food production

Food yield index was used to represent food supply in sample cities. Considering the difference in food demand between urban and rural population (Liu et al., 2022), the food consumption of sample cities was calculated by calculating the sum of per capita

food consumption and permanent population of rural and urban respectively (Nie et al., 2021).

$$F_i = S_i - D_i = S_i - [PFC_j^{urban} \times RP_i^{urban} + PFC_j^{rural} \times RP_i^{rural}] \quad (\text{Eq.1})$$

In Eq.1, i is the sample city of the study; F_i is the food resource in city i ; S_i is the food supply of i city; D_i is the food demand of city i ; PFC_j^{urban} is the per capita urban food consumption of the province where city i is located; PFC_j^{rural} is the per capita rural food consumption in the province where the city is located; RP_i^{urban} is the permanent urban population of city i ; RP_i^{rural} is the permanent rural population of city i . When $F_i > 0$, it indicates that the food supply of the city is greater than the demand, and the food is surplus; on the contrary, it is resource deficit.

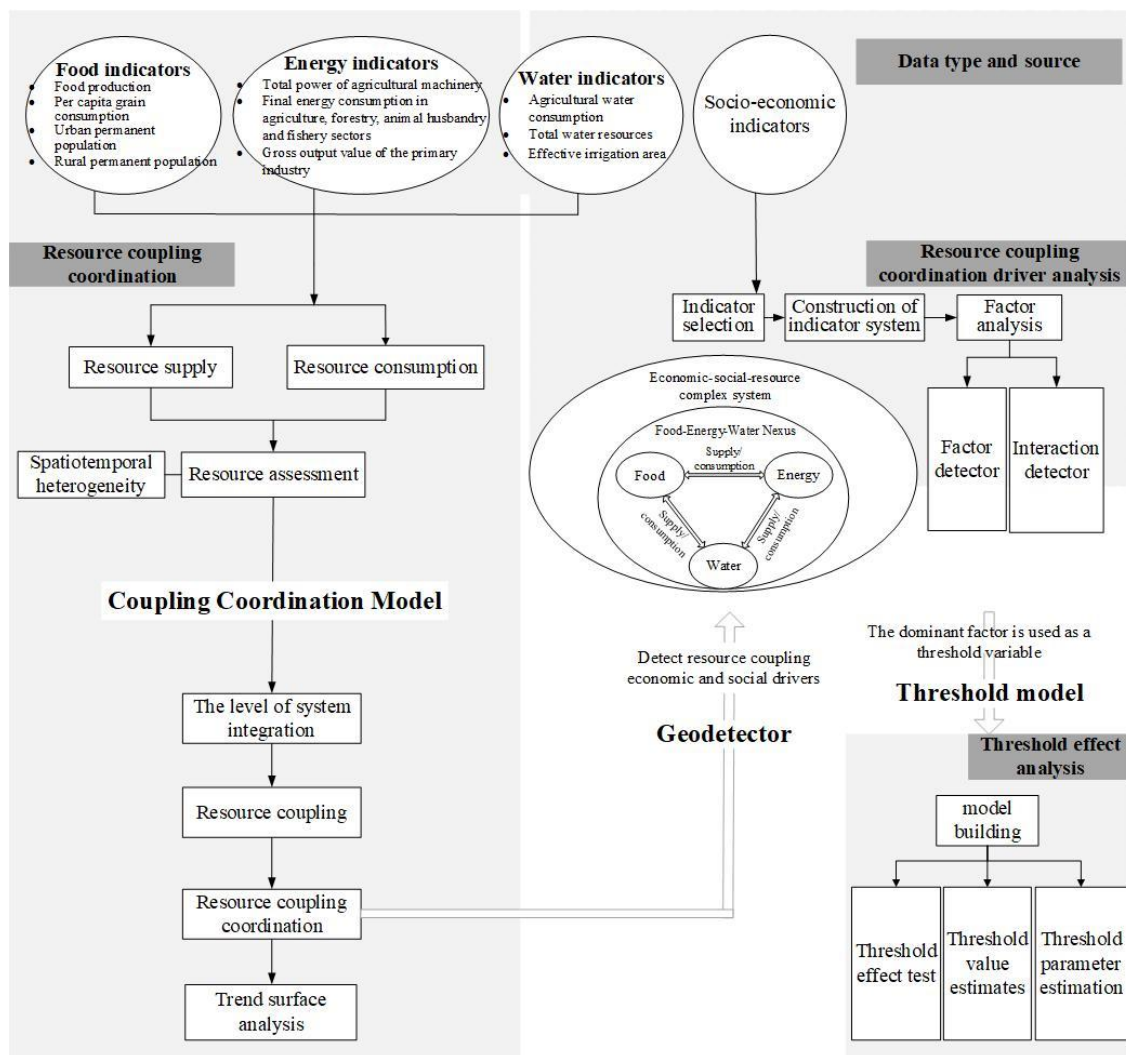


Figure 2. Research framework

Agricultural energy

Agricultural energy input mainly includes pesticides, fertilizers, agricultural film and the total power of agricultural machinery (Luo et al., 2021). In addition to the total power of agricultural machinery, other agricultural energy input factors account for a small proportion and are ignored. Therefore, the proportion of primary gross product in each province is multiplied by the final consumption of energy in agriculture, forestry, animal husbandry and fishery to calculate the agricultural energy demand.

$$E_i = S_i - D_i = AMTP_i - \frac{PIGP_i}{PIGP_j} \times AETC_j \quad (\text{Eq.2})$$

In Eq.2, i is the sample city of the study; j is the province where the sample city is located; E_i is the agricultural energy status of City i ; $AMTP_i$ is the general movement of agricultural machinery in city i which represents the agricultural energy supply; $PIGP_i$ is the gross product of the primary industry of the province where city i is located; $AETC_j$ is the terminal energy consumption of agriculture, forestry, animal husbandry and fishery in province j . When $E_i > 0$, it indicates that the supply of agricultural energy resources in the city is greater than the demand, and agricultural energy resources are in surplus; on the contrary, it is resource deficit.

Agricultural water resources

The proportion of agricultural effective irrigation area multiplied by the total amount of water resources is used to calculate the agricultural water supply and the statistical data of agricultural water consumption and use.

$$W_i = S_i - D_i = TWR_i \times \frac{EIA_i}{CA_i} - AWC_i \quad (\text{Eq.3})$$

In Eq.3, W_i is the agricultural water resource in city i ; TWR_i is the total water resources of city i ; EIA_i is the effective irrigated area of urban agriculture in city i ; CA_i is the administrative area of city i ; AWC_i is the agricultural water resources consumption of city i . When $W_i > 0$, it indicates that the supply of agricultural water resources in the city is greater than the demand, and agricultural water resources are in surplus; on the contrary, it is resource deficit.

Measurement of "Food-Energy-Water Nexus"

The coupling coordination degree model, geographical detector and threshold model are used to evaluate and analyze the coupling coordination development of agricultural resources in the Loess Plateau of China, and identify the influencing factors and their nonlinear relations and inflection points. The coupling coordination degree model is used to measure the degree of interdependence and restriction among systems, and reflects the coupling coordination development state of the system. The coupling of food, energy and water resources is essential for sustainable and high-quality development in the region. In order to evaluate the coupling coordination degree of food, agricultural energy and agricultural water resources in the Loess Plateau of China,

the coupling coordination degree model was used for quantitative analysis to reveal the coupling coordination development of agricultural resources.

Geodetector is a statistical method used to study the differentiation of geographical space and reveal the influencing factors behind it. It determines the influence of these factors on the spatial distribution of a thing by detecting the consistency between the distribution of these factors and the distribution of the thing. The influence degree of economic and social factors on the coupling coordination degree of agricultural resources in Loess Plateau of China was investigated by using geographic detector, and the main influencing factors were screened out.

Threshold model is a nonlinear econometric model used to study the nonlinear relationship and inflection point between the explanatory variable and the explained variable. It finds the threshold variables, estimates the threshold value based on the sample data, and tests whether the parameters of the sample group divided according to the threshold value have significantly different changes. Threshold model breaks through the traditional econometric model of the assumption of independent objects, and improves the depth and breadth of research. This paper analyzes the threshold effect of the factors influencing the coordination degree of agricultural resources coupling from the perspective of nonlinear threshold.

The coupling coordination degree model is used to study the effects of subsystems (Zhou et al., 2022). In the Loess Plateau of China, the coupling coordination degree model is used to calculate the coupling coordination degree of urban agriculture's food, energy, and water resources. The coupling coordination degree assessment results are then utilized to study the subsequent influencing elements. Conduct dimensionless treatment on the food, agricultural energy and agricultural water resources (Qi et al., 2021).

$$y_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \quad (\text{Eq.4})$$

In *Eq.4*, i represents the study sample city; j represents the food resource (F), agricultural energy (E) and agricultural water resources (W); y_{ij} indicates the standardized value of resource status, ranging from 0 to 1; x_{ij} is the resource j of city i ; $\max x_{ij}$ indicates the maximum value of the current resource; $\min x_{ij}$ is the minimum value of resource status.

After calculating the evaluation index of each subsystem, the comprehensive evaluation index of urban agricultural food, energy and water resources in the Loess Plateau of China was calculated (Cui et al., 2022).

$$T = \sqrt[3]{F \times E \times W} \quad (\text{Eq.5})$$

In *Eq.5*, F , E and W respectively represent the standardized values of food, agricultural energy and agricultural water resources. T represents the comprehensive evaluation index of food, agricultural energy and agricultural water resources to reflect the sustainable development of resources. The value interval of the comprehensive evaluation index is $[0,1]$. The closer T value is to 1, the higher the comprehensive level of food resources, agricultural resources and agricultural water resources is.

Coupling degree and coupling coordination degree were used to quantitatively analyze the coupling coordination relationship among food, agricultural energy and agricultural water resources (Ding and Deng, 2022; Sun et al., 2022; Wang et al., 2023; Jing et al., 2023).

$$C = \frac{3\sqrt[3]{(F \times E \times W)}}{(F + E + W)} \quad (\text{Eq.6})$$

In Eq.6, C represents the degree of coupling, indicating the degree of interaction and mutual influence between food, agricultural energy and agricultural water resources. The value interval of coupling degree is $[0,1]$, and the closer C value is to 1, the stronger the interaction between food, agricultural energy and agricultural water resources is. The coupling degree model can reflect the strength of coupling effect, but cannot reflect the difference of coordination development level, so the coupling coordination degree model is constructed.

$$D = \sqrt{C \times T} \quad (\text{Eq.7})$$

In Eq.7, D represents the coupling coordination degree of food, agricultural energy and agricultural water resources. The value interval of coupling degree is $[0,1]$, and the closer D value is to 1, the higher the coordinated development level of food, agricultural energy and agricultural water resources is. According to the existing research results, the types of coupling coordination degree is shown in Table 2 (Cheng et al., 2019; Ding and Deng, 2022; Wang et al., 2023).

Table 2. Types of coupling coordination and judgment criteria

Coordination types	Coupling coordination degrees		Coupling coordination types
Coordinated development Categories	High coordination	0.90-1.00	Quality coordination
		0.80-0.89	Good coordination
	Basic coordination	0.70-0.79	Imminent coordination
		0.60-0.69	Primary coordination
Overclass Category	Excessive	0.50-0.59	Barely coordination
		0.40-0.49	Imminent imbalance
Dysrecessionary category	Dysrecessionary	0.00-0.39	Imbalance

Spatial trend surface

To better reveal the spatial and temporal pattern and its internal mechanism of the coupling coordination degree of resources in the Loess Plateau of China, the spatial trend surface was used to simulate the spatial pattern and evolution trend of geographical elements. Vertical bar in the spatial trend plane represents the resource coupling coordination degree of each sample point, and these points are projected onto an east-west and north-south orthogonal plane, and a best fitting line is drawn through the projection point to simulate the change trend in a specific direction (Yang et al., 2018) (See Formula (1) in APPENDIX).

Geodetector

Geodetector is a statistical method that reveals the driving force of factors by detecting the spatial differentiation of geographical elements. Assuming that a factor has a significant influence on the dependent variable, it is similar to the dependent variable in spatial distribution (Jing et al., 2023). The geodetector method can detect the driving force of a single impact factor as well as the driving force of the interaction of two factors on the dependent variable, and there is no linear hypothesis or normal distribution hypothesis (Song et al., 2020; Liu et al., 2021). The analysis of geodetector includes factor detection and interaction detection. Factor detection studies the spatial differentiation of dependent variables and the driving force of different factors on dependent variables. The driving force degree is measured by q value. Interaction probe analyzes the interaction of different influence factors and evaluates the driving force changes of interaction on dependent variables (See *Formula (2)* in APPENDIX).

Sustainable development is not only limited by the degree of resource scarcity, but also by the level of social and economic development (Zand et al., 2019). The economic evaluation index of the coupling coordination degree of agricultural food, energy and water resources is measured by the per capita GDP (PGDP), the total power of agricultural machinery (AMPT), and the general budget expenditure of local finance (LGBE), while the social evaluation index is measured by the permanent population (RP), the proportion of education expenditure in GDP (EPGEP), and the urbanization rate (UR). According to the quantile method (Wang et al., 2016), the six factors of per capita GDP, the proportion of education expenditure in GDP, the total power of agricultural machinery, the resident population, the general budget expenditure of local finance, and the urbanization rate are divided into five categories from low to high. The five categories from high to low are assigned as 1, 2, 3, 4 and 5 respectively, which are used as independent factor input models, and the coupled coordination degree of agricultural food-energy-water resources is used as dependent variable input model to explore the driving factors of the coupled coordination degree of resources in the Loess Plateau of China.

Spatial autocorrelation model

Bivariate local spatial autocorrelation results can reflect the spatial aggregation and differentiation characteristics among variables, and identify the spatial variation characteristics of trade-offs and synergies between variables (Ding et al., 2022) (See *Formula (3)* in APPENDIX).

Threshold effect model

Explanatory variables and threshold variables

When Geodetector detect the influence of single economic and social factors on resource coupling coordination degree, it is easy to ignore the combined effect of multiple factors, and over-strengthen or weaken the importance of some factors. According to the degree of importance of all factors, the comprehensive factors of economic development were constructed as explanatory variables to fully reflect the relationship between economic development and resource coupling coordination degree. The calculation formula is as *Eq.8*.

$$\begin{aligned} \text{Economic development} = & \text{per capita GDP} \times 0.089 + \text{proportion of} \\ & \text{educational expenditure in GDP} \times 0.251 + \text{total power of agricultural} \\ & \text{machinery} \times 0.299 + \text{permanent population} \times 0.177 + \text{general budget} \\ & \text{expenditure of local finance} \times 0.075 + \text{urbanization rate} \times 0.110, 0 < \\ & \text{economic development} < 1 \end{aligned} \quad (\text{Eq.8})$$

In the context of rural revitalization, agricultural modernization, education level and labor force play an important supporting role in the high-quality development of agricultural economy, which is of great practical significance for promoting the high-quality development of agricultural economy in the Loess Plateau of China (Sun et al., 2023). The threshold variables select geodetector factor to detect the leading factors, the proportion of education expenditure in GDP, the total power of agricultural machinery and the variables of permanent population. The threshold variables is used to investigate whether the impact of economic development on resource coupling coordination degree has phased characteristics under different levels of education, agricultural technology and population.

Cross-sectional threshold model

The influence of single factor on resource coupling and coordination is studied by geodetector, and the degree of resource coupling and coordination is jointly affected by various factors. The threshold model is further used to study the influence of comprehensive factors of economic development on resource coupling coordination degree under the role of leading factors, which is helpful to further study the high-quality economic development, reasonably understand the nonlinear relationship between economic development and resource coupling coordination, and realize the important role played by important factors.

Refer to Hansen (2000) cross-sectional threshold model to study the nonlinear influence relationship between economic development level and resource coupling coordination degree, and the formula is as follows.

$$\begin{aligned} Couple_i = & \alpha + \beta_1 Economic_i I(AMTP_i \leq q_2) + \beta_2 Economic_i I(q_1 < AMTP_i \leq q_2) + \\ & \beta_3 Economic_i I(AMTP_i > q_1) + e_i \end{aligned} \quad (\text{Eq.9})$$

In Eq.9, *Couple* is the coupling coordination degree of explained variables. *AMTP* is the threshold variable total power of agricultural machinery; *q* is the threshold value; *Economic* is the explanatory variable economic development level; β_1 and β_2 are the coefficient; α and e_i are constant terms and random disturbance terms, respectively. *I* is the indicator function, which takes the value 1 if the expression in parentheses is satisfied, and 0 otherwise.

Results

Food production

The food production in the Loess Plateau of China has significant spatial differentiation characteristics. The areas with higher food surplus were mainly distributed in the areas with low terrain and superior agricultural production conditions.

Among them, Taiyuan is a big agricultural province, but as the capital city, the urban population is large consumption, resulting in food supply is less than the food demand. From 2000 to 2020, food surplus showed an upward trend, showing a spatial distribution of supply exceeding demand. In 2020, only a few cities were in food deficit, including Taiyuan City, Lanzhou City and Wuhai City. From 2000 to 2020, the average food deficit of these three cities was -240,200 tons, -68,700 tons and -23,300 tons, respectively. The reason was that food consumption exceeds food production, the population was large but agricultural production conditions are poor. In Haibei Tibetan Autonomous Prefecture, Hainan Tibetan Autonomous Prefecture, Huangnan Tibetan Autonomous Prefecture, Haidong City, Linxia Hui Autonomous Prefecture, Zhongwei City, Tianshui City, Yangquan City, Xining City and Luliang City, the food status changed from short supply at the beginning of the period to food surplus at the end of the study period. The changes of grain supply and demand in these areas are the result of both technology and policy.

First, engineering measures such as building terraces and silting DAMS not only increase the available land resources in the area, but also help to increase crop yield per unit area. Second, the machinery subsidy policy can effectively improve the level of agricultural mechanization, so that advanced agricultural production technology can be widely and rapidly promoted and applied, and then improve agricultural productivity; Third, policies such as the abolition of agricultural taxes are conducive to promoting the enthusiasm of farmers, and the implementation of these policies has promoted the growth of grain production for many years. Among them, five cities in Qinghai province, Haibei Tibetan Autonomous Prefecture, Hainan Tibetan Autonomous Prefecture, Huangnan Tibetan Autonomous Prefecture, Xining City and Haidong City, all changed from grain deficit at the beginning to grain surplus at the end of the period, because in recent years, Qinghai Province has been actively implementing the spirit of the National Agricultural Modernization Plan (2016-2020). Vigorously promote the province's agricultural modernization. In this process, the work of "three agriculture and three animal husbandry" has been placed in the position of "top priority", and the policy of strengthening agriculture, benefiting agriculture and enriching peasants has been constantly improved.

Agricultural energy

The spatial distribution of the agricultural energy varied greatly, and the fragmented change map spots were widely distributed. From 2000 to 2020, the agricultural energy was in deficit, and the degree of deficit increased significantly. In 2020, the city with the worst agricultural energy deficit was Yuncheng, with a shortfall of 736,500 tons of standard coal. In addition, Cities with serious shortage were Bayannur (-491,200 tons of standard coal), Xianyang (-405,700 tons of standard coal), Wuzhong (-380,400 tons of standard coal), Linfen (-346,300 tons of standard coal), Hohhot (-325,500 tons of standard coal), Changzhi (-307,600 tons of standard coal), Xinzhou (-305,300 tons of standard coal), Xi'an (-301,600 tons of standard coal), and the energy deficit of other cities was between 0-300,000 tons of standard coal. The urban agricultural energy resources in the Loess Plateau of China was deficit, which was the basic problem of regional sustainable development. The conclusion is consistent with the research results of the Scholar, which shows that energy shortage is the most common constraint in the country (Feriha et al., 2015). Compared with other provinces, Qinghai's agricultural energy gap is small, including Xining City, Haidong City, Haibei Tibetan Autonomous

Prefecture, Hainan Tibetan Autonomous Prefecture, Huangnan Tibetan Autonomous Prefecture, which is closely related to Qinghai's low economic level and low agricultural energy consumption.

Agricultural water resources

From 2000 to 2020, agricultural water resources were in deficit, and only a few urban agricultural water resources were in surplus, including the cities with relatively high current agricultural water resources were mainly distributed in the southeast region of the Loess Plateau of China with low terrain, such as Sanmenxia, Jiyuan City and Tongchuan City (*Figure 3*). In 2020, the agricultural water resources were positive in Tongchuan City, Hainan Tibetan Autonomous Prefecture, Sanmenxia City, Jiyuan City, Huangnan Tibetan Autonomous Prefecture and Haidong City, while the water resources in other cities were negative. Bayannur City had the most serious water shortage, with 4.78 billion cubic meters of water shortage. Followed by Yinchuan (-1.694 billion cubic meters), Wuzhong (-1.66 billion cubic meters), Zhongwei (-1.266 billion cubic meters), Yuncheng (-1.229 billion cubic meters), Ordos (-1.083 billion cubic meters), Shizuishan (-1.027 billion cubic meters), Other cities had water shortages of 0-1 billion cubic meters. From 2000 to 2020, the cities of Hainan Tibetan Autonomous Prefecture and Haidong City changed from shortage to surplus of agricultural water resources.

Analysis of Food-Energy-Water Nexus

The spatial distribution of coupling coordination degree of food, agricultural energy, and agricultural water resources in 44 cities in the Loess Plateau of China was relatively dispersed, with significant spatio-temporal differentiation (*Figure 3*). From 2000 to 2020, the overall distribution characteristics of urban resource coupling coordination degree were relatively stable, and most cities had coordinated development degree. The regions with the highest coupling coordination degree were Luoyang City, Baoji City and Weinan City, which were in a good coordination state from 2000 to 2020, and the mean coupling coordination degree was 0.88, 0.85 and 0.85, respectively. The lowest areas were Bayannur City, Yuncheng City and Taiyuan City, which were in the state of dissonant decline from 2000 to 2020, and the mean coupling coordination degree was 0.20, 0.11 and 0.10, respectively. From 2000 to 2020, the types of coupling coordination degree of agricultural food, energy and water resources changed, and the coupling coordination degree level of Lanzhou City, Xining City, Yangquan City, Zhongwei City, Luliang City, Haidong City, Changzhi City, Datong City, Jinzhong City, Tianshui City, Linfen City, Shuozhou City, Xinzhou City, Dingxi City, Qingyang City and Linxia Hui Autonomous Prefecture increased. The level of resource coupling coordination in Yinchuan City, Wuzhong City, Baoji City, Yan 'an City, Xianyang City, Xi 'an City, Weinan City, Hohhot City, Zhengzhou City and Jiyuan City declined. At present, the cities below the barely coordinated type were mainly distributed in the eastern part of the Loess Plateau of China.

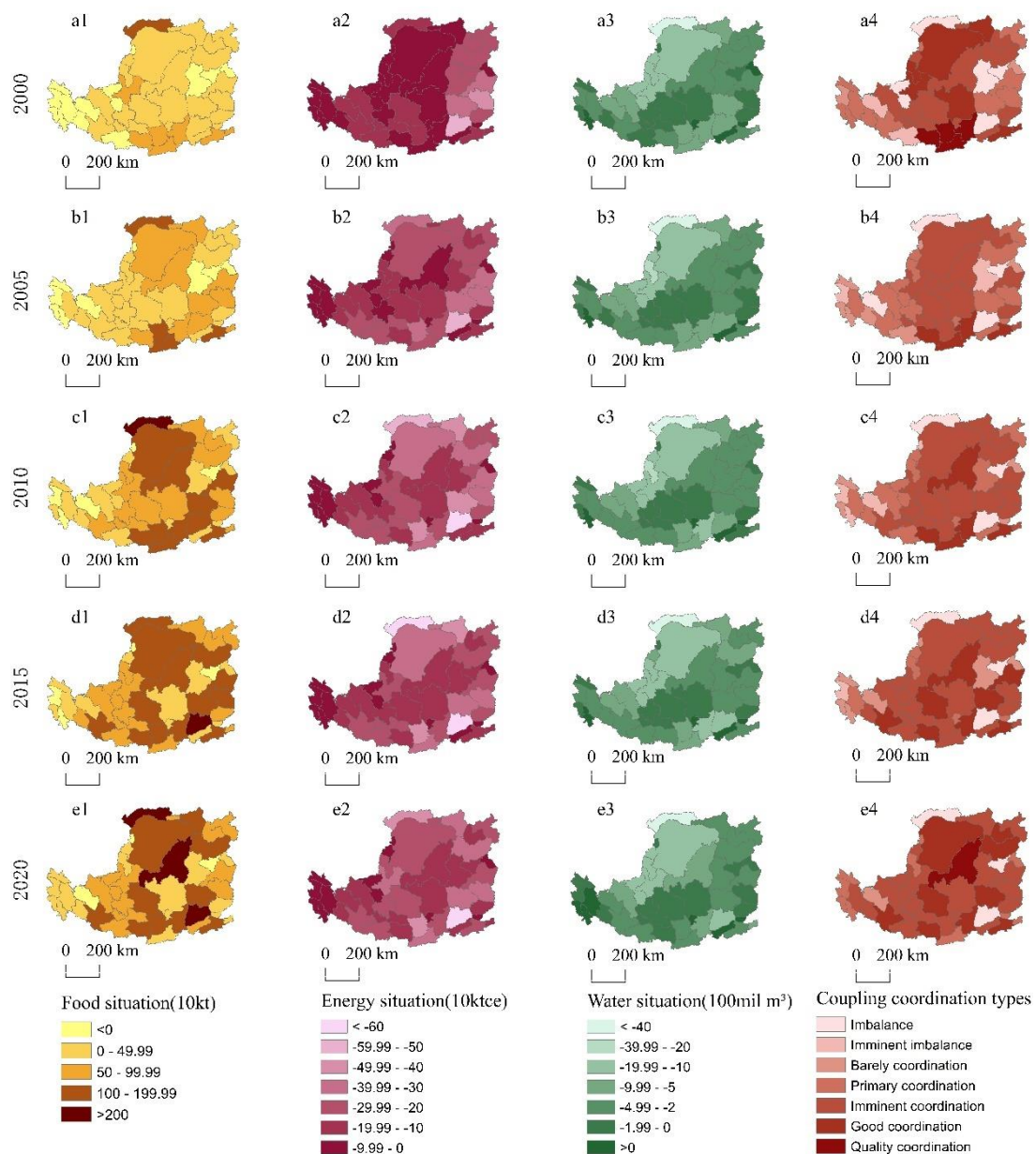


Figure 3. Spatial pattern of agricultural resource stock and resource coupling coordination degree in the Loess Plateau of China from 2000 to 2020

Analysis of influencing factors

Factor detection and interactive detection

The influence of economic and social factors on the coupling coordination degree of agricultural food, agricultural energy and agricultural water resources in the Loess Plateau of China in 2000 and 2020 was studied by using the factor detection and interactive detection modules of the geodetector (Figure 4). In 2000, the influencing factors of resource coupling coordination degree were successively permanent population (0.386) > education expenditure in GDP (0.355) > per capita GDP (0.283) >

urbanization rate (0.257) > general budget expenditure of local finance (0.228) > total power of agricultural machinery (0.100). Permanent population was the largest influencing factor. The influencing factors of resource coupling coordination degree in 2020 were successively permanent population (0.345) > per capita GDP (0.312) > total power of agricultural machinery (0.260) > proportion of education expenditure in GDP (0.250) > urbanization rate (0.244) > general budget expenditure of local finance (0.184). Permanent population remains the biggest factor in 2020. In 2000 and 2020, the P-value of permanent resident population and per capita GDP remained stable, ranking first and second, which are important factors affecting the coupling and coordination of agricultural resources.

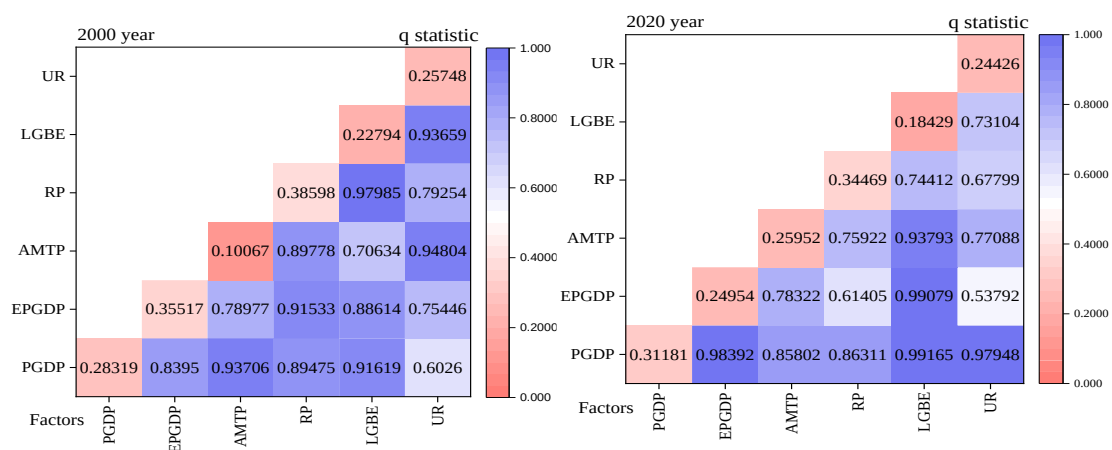


Figure 4. Factor detection results of urban resource coupling coordination degree in the Loess Plateau of China in 2000 and 2020

Compared with 2000, the explanatory power of total power factor of agricultural machinery to coupling coordination degree increased in 2020, from the sixth in 2000 to the third in 2020. The explanatory power of the proportion of education in GDP on coupling coordination degree decreased, from the third place in 2000 to the fourth place in 2020. In summary, permanent population, per capita GDP and total power of agricultural machinery were the leading factors affecting the coupling and coordination of resources. The future development planning and management of agricultural land and water resources should be paid attention to.

The purpose of interaction detection is to analyze and compare the synergistic effect of any two influencing factors on the coupling coordination degree of agricultural resources with the effect generated when each single influencing factor acts independently. The interaction detection results showed that the interaction of any two impact factors on the coupling coordination degree was greater than the independent effect of a single impact factor, and the interaction enhancement relationship of factors was nonlinear enhancement (Table 3). In 2000 and 2020, the interaction between per capita GDP and local general budget expenditure ranked top and was greater than 0.9, and ranked first in 2020, which were the two factors with the strongest interaction. The dual effect of the two factors played a decisive role in the coupling and coordinated development of agricultural food, energy and water resources.

Table 3. Interaction detection types of urban resource coupling coordination degree in the Loess Plateau of China

Interaction factors	The year 2000		The year 2020	
	Q value	Type	Q value	Type
Urbanization rate∩Permanent population	0.793	Nonlinear enhancement	0.678	Nonlinear enhancement
Urbanization rate∩Proportion of education expenditure in GDP	0.754	Nonlinear enhancement	0.538	Nonlinear enhancement
Urbanization rate∩GDP per capita	0.603	Nonlinear enhancement	0.979	Nonlinear enhancement
Urbanization rate∩General budget expenditure of local finance	0.937	Nonlinear enhancement	0.731	Nonlinear enhancement
Urbanization rate∩Total power of agricultural machinery	0.948	Nonlinear enhancement	0.771	Nonlinear enhancement
Permanent population∩Proportion of education expenditure in GDP	0.915	Nonlinear enhancement	0.614	Two-factor enhancement
Permanent population∩GDP per capita	0.895	Nonlinear enhancement	0.863	Nonlinear enhancement
Permanent population∩General budget expenditure of local finance	0.980	Nonlinear enhancement	0.744	Nonlinear enhancement
Permanent population∩Total power of agricultural machinery	0.898	Nonlinear enhancement	0.759	Nonlinear enhancement
Proportion of education expenditure in GDP∩GDP per capita	0.840	Nonlinear enhancement	0.984	Nonlinear enhancement
Proportion of education expenditure in GDP∩General budget expenditure of local finance	0.886	Nonlinear enhancement	0.991	Nonlinear enhancement
Proportion of education expenditure in GDP∩Total power of agricultural machinery	0.790	Nonlinear enhancement	0.783	Nonlinear enhancement
GDP per capita∩General budget expenditure of local finance	0.916	Nonlinear enhancement	0.992	Nonlinear enhancement
GDP per capita∩Total power of agricultural machinery	0.937	Nonlinear enhancement	0.858	Nonlinear enhancement
General budget expenditure of local finance∩Total power of agricultural machinery	0.706	Nonlinear enhancement	0.938	Nonlinear enhancement

Bivariate spatial autocorrelation

(1) Analysis of bivariate local spatial autocorrelation between agricultural resource coupling coordination degree and total mechanical power

Total power of agricultural machinery and agricultural resources coupling coordination bivariable LISA cluster graph in 2000 and 2020 (*Figure 5*). In 2000 and 2020, the coupling coordination degree of agricultural resources and the total power of agricultural machinery showed a high-high agglomeration coordination type. In 2000, it was located in Changzhi City, Linfen City, Weinan City, Sanmenxia City, Jiyuan City and Zhengzhou City. By 2020, it was located in Baotou City, Tongchuan City and Sanmenxia City, which were in low-lying areas conducive to mechanization, rich resource supply and conducive to agricultural development. These regions have high agricultural technology level and resource allocation efficiency, making them leading regions in agricultural development. In 2020, compared with 2000, the synergy area was reduced, and only Sanmenxia city was in a state of high-high agglomeration synergy.

Low-low, low-high, high-low clustering types scattered distribution. In 2000, Xining City and Haidong City were low-low coordinated development area. In 2000, Yuncheng City was the low-high tradeoff development area. In 2020, Xi 'an and Zhengzhou were the low-high tradeoff development areas. In 2000, Shizuishan City was the high-low tradeoff development area. In 2020, Haidong City was the high-low tradeoff development area. There was no significant correlation between the coupling coordination degree of agricultural resources and the total mechanical power in other regions. In 2020, compared with 2000, the intensity of spatial agglomeration decreased.

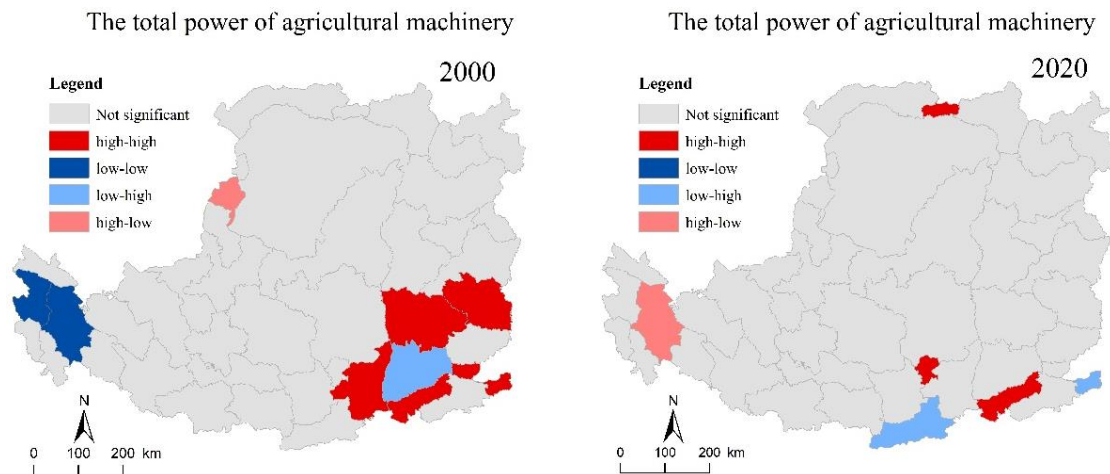


Figure 5. The LISA cluster diagram of the resource coupling coordination degree and the total power of agricultural machinery

(2) Local spatial autocorrelation analysis between agricultural resource coupling and coordination degree and per capita GDP

LISA cluster graph of coupling coordination degree of agricultural resources and per capita GDP in 2000 and 2020 (Figure 6). The spatial pattern of agricultural resource coupling coordination degree and per capita GDP was relatively stable in 2000 and 2020. The spatial agglomeration of high-high agglomeration synergies has increased from Ordos, Baotou, Shizuishan and Luoyang in 2000 to Ordos, Baotou, Shizuishan, Luoyang, Hohhot and Shuozhou in 2020. From 2000 to 2020, the coupling coordination degree of agricultural resources and per capita GDP of Ordos City, Baotou City, Shizuishan City and Luoyang City showed a state of high-high agglomeration coordinated development. These cities not only had a high coupling coordination degree of agricultural resources, but also had a high economic level, so they became demonstration cities of agricultural development. The low-low agglomeration synergy type was Lanzhou and Tianshui in 2000, and Lanzhou, Xining, Hainan Tibetan Autonomous Prefecture and Huangnan Tibetan Autonomous Prefecture in 2020. In 2000 and 2020, both the coupling coordination degree of agricultural resources and per capita GDP of Lanzhou presented a state of low-low agglomeration coordinated development. The city not only had a low coupling coordination degree of agricultural resources, but also a low level of economic development, making it a key region for agricultural development. The low-high agglomeration type was Bayannur City and Wuhai City in 2000, and Bayannur City, Wuhai City and Yinchuan City in 2020. The high-low agglomeration type was Yan 'an City, Qingyang City, Guyuan City, and

Pingliang City in 2000, and Guyuan City, Pingliang City, Baiyin City, Tianshui City, and Haidong City in 2020. There was no significant correlation between the coupling coordination degree of agricultural resources and per capita GDP in other regions.

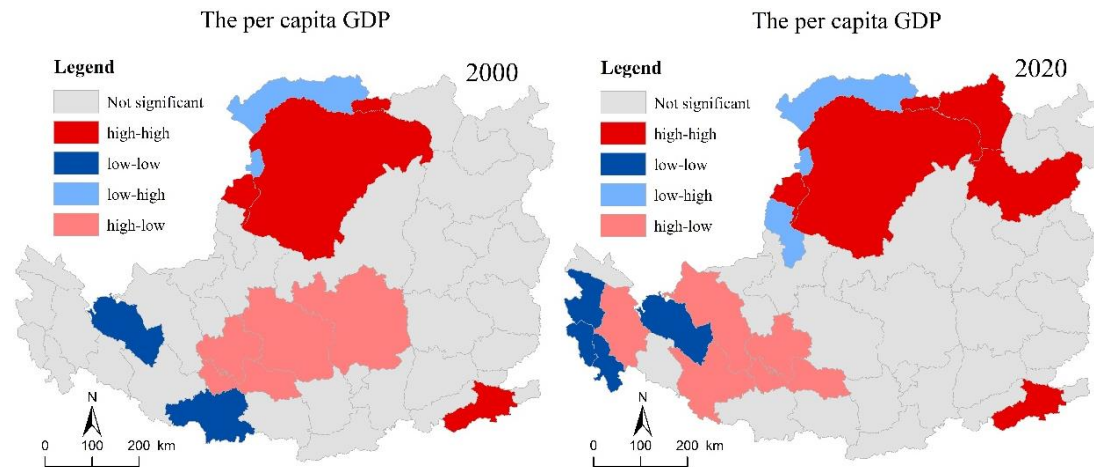


Figure 6. The LISA cluster diagram of resource coupling coordination degree the permanent residents and the per capita GDP

(3) Local spatial autocorrelation analysis between the coupling coordination degree of agricultural resources and the resident population

In 2000 and 2020, the coupling coordination degree of agricultural resources and the proportion of educational expenditure in GDP mainly showed high-high and low-low coordination types (Figure 7). The significant high-high cooperative cities were mainly distributed in the southeastern part. In 2000, Xi'an City, Baoji City, Weinan City, Sanmenxia City, Jiyuan City, and Zhengzhou City were Significant high-high collaborative cities. In 2020, the spatial distribution characteristics of the coupling coordination degree of agricultural resources and the proportion of education expenditure in GDP of high-high coordinated development disappeared. The significant low-low cooperative cities were mainly distributed in the Southwest part. In 2000, Xining City, Haidong City, Huangnan Tibetan Autonomous Prefecture and Hainan Tibetan Autonomous Prefecture were low-low cooperative cities. In 2020, the low-low agglomeration characteristics of Haidong City and Hainan Tibetan Autonomous Prefecture disappeared. In 2000 and 2020, Xining City and Huangnan Tibetan Autonomous Prefecture showed a state of low-low coordinated development. In 2020, Zhengzhou City showed significant low-high tradeoff development. Ordos City and Yinchuan City in 2000 and Guyuan City in 2020 were significant high-low tradeoff development area. There was no significant correlation between permanent population and resource coupling in other regions.

Threshold value estimation

(1) Threshold effect test

The threshold effect test refers to the phenomenon that when an economic parameter reaches a specific value, it causes another economic parameter to suddenly shift to other forms. With the single, double and triple threshold effect test results of the total power

of agricultural machinery, permanent population and per capita GDP as threshold variables, the influence of the comprehensive index of economic development on the coupling coordination degree of agricultural resources under different threshold values was investigated. The corresponding critical value of F statistic at the significance level of 1%, 5% and 10% (Table 4), p value less than 0.1 indicates the existence of threshold effect. With the total power of agricultural machinery and resident population as threshold variables, the p values of single threshold and double threshold were less than 0.1, passing the significance level test of 1%, indicating that when the total power of agricultural machinery and resident population are taken as thresholds, there was a nonlinear relationship between economic development and resource coupling and coordination, and there was a double threshold effect. When per capita GDP was taken as the threshold variable, the p values of single threshold, double threshold and triple threshold were all less than 0.1, which failed the significance level test, indicating that there is no threshold effect when per capita GDP was taken as the threshold variable.

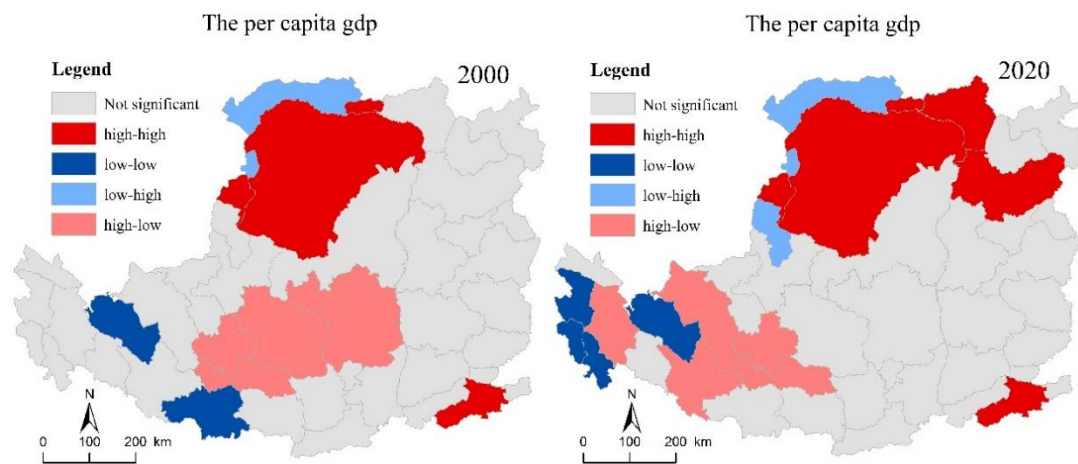


Figure 7. The LISA cluster diagram of the resource coupling coordination degree and the permanent residents

Table 4. The threshold effect test of the Loess Plateau of China

Threshold variables	Threshold numbers	F value	P value	Sampling	Critical value		
					10%	5%	1%
Total power of agricultural machinery	Single threshold	7.419***	0.010	300	7.656	3.930	2.581
	Double threshold	23.004**	0.017	300	39.882	3.149	1.956
	Triple threshold	1.540	0.257	300	6.789	4.310	3.027
Permanent population	Single threshold	3.530*	0.070	300	9.478	4.288	3.005
	Double threshold	5.784**	0.020	300	7.371	4.608	3.229
	Triple threshold	0.001	0.963	300	12.343	5.485	3.206
GDP per capita	Single threshold	2.046	0.163	300	7.524	4.048	2.781
	Double threshold	2.031	0.183	300	12.500	5.299	3.658
	Triple threshold	2.590	0.123	300	10.365	4.013	3.043

Note: Threshold value $P < 0.1$, indicating the existence of threshold effect

(2) Threshold value estimation

The single-threshold and double-threshold models are used to study the nonlinear impacts of influencing factors on the coupling coordination degree of agricultural resources. The estimation results in *Table 5* showed that under 95% confidence interval, when the total power of agricultural machinery was taken as the threshold variable, there was a double threshold. The estimated values of the two thresholds were 59.48 and 566.30 respectively, and the corresponding confidence intervals were [55.470, 247.842] and [566.300, 566.300]. When the resident population was taken as the threshold variable, there was a double threshold, and the estimated values of the two thresholds are 159.14 and 468.87, respectively, and the corresponding confidence intervals were [131.792, 362.475] and [268.354, 1261.680].

Table 5. The estimated results of threshold value

Threshold Variables	Threshold numbers	Threshold estimate	95% confidence interval
Total power of agricultural machinery	Single threshold	59.48	[55.470, 247.842]
	Double threshold	566.30	[566.300, 566.300]
Permanent population	Single threshold	159.14	[131.792, 362.475]
	Double threshold	468.87	[268.354, 1261.680]

(3) Threshold parameter estimation

In order to systematically explore whether there are obvious periodic evolution laws in the impacts of the total power of agricultural machinery and the comprehensive evaluation index of economic development on the coupling coordination degree of agricultural resources in the Loess Plateau region under different threshold settings, as well as the potential nonlinear action mechanisms behind them. The threshold model still selects *Eq.9* and the estimation results showed that the influence of different threshold total power of agricultural machinery and economic development level on the coupling coordination degree of urban agricultural resources in the Loess Plateau of China has stage characteristics (*Table 6*). Under the influence of agricultural machinery level, economic development had significant trade-off effect on resource coupling coordination. The single threshold regression results showed that when the total power of agricultural machinery was less than 594,800 KWH, the coefficient of economic development level on resource coupling coordination degree was -0.852, and significantly negative at the 5% level. When the total power of agricultural machinery was greater than 594,800 KWH, the coefficient of economic development level on resource coupling coordination degree was -0.109, the negative effect decreased, the agricultural technology level and resource utilization efficiency increased, and the inhibition effect of economy on resource coupling coordination decreased.

The double threshold regression results showed that when the total power of agricultural machinery was less than 594,800 KWH, the coefficient of economic development level on resource coupling coordination degree was -0.872, and was significantly negative at 1% level. The total power of agricultural machinery was greater than 5.6630 million KWH, and the coefficient of economic development level on resource coupling coordination degree was -1.625, which was significantly negative at 1% level. Economic development level had a strong negative effect on resource coupling coordination degree. When the total power of agricultural machinery was between 59.48 and 566.30, the coefficient of economic development level on the

coupling coordination degree of agricultural resources was -0.067, which did not pass the significance test. The inhibitory effect of economic development level on the coupling coordination degree of agricultural resources was the least. When the total power of agricultural machinery was within a certain threshold range, the economic development level had the least trade-off effect on the resource coupling coordination degree, showing a weak negative effect, indicating that there was indeed a nonlinear relationship between economic development and resource coupling coordination degree in the Loess Plateau of China, which was consistent with the empirical conclusions and theoretical assumptions above. The reason was that the total power input of agricultural machinery was moderate, the utilization rate of resources was improved, and the agricultural economic development and resource coupling coordination were in a relatively harmonious state.

Table 6. Threshold regression model parameter estimation results of the total power of agricultural machinery

Explanatory variables	Single threshold	Double threshold
Economic development*I (Total power of agricultural machinery<59.48)	-0.853** (-2.64)	
Economic development*I (Total power of agricultural machinery>=59.48)	-0.109 (-0.84)	
Economic development*I (Total power of agricultural machinery<59.48)		-0.872*** (-3.28)
Economic development*I (59.48<=Total power of agricultural machinery<566.30)		-0.067 (-0.62)
Economic development*I (Total power of agricultural machinery>=566.30)		-1.625*** (-4.67)
Constant	0.763*** -16.06	0.768*** -19.68
r ²	0.150	0.442
F	3.619	10.560
N	44	44

Note: *, **, and *** refer statistically significance at 10%, 5%, and 1% level, respectively

Threshold model estimation results showed that the impact of different threshold permanent population and economic development level on the coupling coordination degree of urban agricultural resources had stage characteristics (Table 7). Under the influence of permanent population, economic development had a significant trade-off effect on resource coupling and coordination. The single threshold regression results showed that the coefficient of economic development level on resource coupling coordination degree is -0.768 and significantly negative at the 10% level when the permanent population was less than 1,591,400. When the permanent population was greater than 1,591,400 people, the coefficient of economic development level on resource coupling coordination degree was -0.290, and the negative effect decreased.

The study on the influence of single factor on the explained variable only shows the direct influence of economic development factors on the degree of resource coupling coordination, but cannot fully reveal the influence of influencing factors. Therefore, we should pay attention to the influence of economic development on the degree of resource coupling coordination under the constraints of various factors, otherwise the correct result will be overturned.

Table 7. Threshold regression model parameter estimation results of the permanent residents

Explanatory variables	Single threshold	Double threshold
Economic development*I (resident population<159.14)	-0.768* (-1.80)	
Economic development*I (resident population>=159.14)	-0.290 (-1.12)	
Economic development*I (resident population<159.14)		-0.131 (-0.27)
Economic development*I (159.14<=resident population<468.87)		0.331 -0.91
Economic development*I (resident population>=468.87)		-0.223 (-0.90)
Constant	0.817*** -9.72	0.674*** -6.64
r ²	0.081	0.187
F	1.796	3.074
N	44	44

Note: *, **, and *** refer statistically significance at 10%, 5%, and 1% level, respectively

The results of double threshold regression showed that economic development has a significant trade-off effect on resource coupling and coordination under the influence of permanent population. When the total power of agricultural machinery was less than 1,591,400 people, the coefficient of economic development level on resource coupling coordination degree was -0.132. When the permanent population was greater than 4,688,700, the coefficient of economic development level on resource coupling coordination degree was -0.223, and the negative effect of economic development level on resource coupling coordination degree was enhanced. When the permanent population ranges from 159.14 to 468.87, the coefficient of economic development level on the coupling coordination degree of agricultural resources is 0.331, which did not pass the significance test. Economic development level had a positive impact on the coupling coordination degree of agricultural resources. When the permanent population was within a certain threshold range, the economic development level played a promoting role in the resource coupling coordination degree. The reason was that with the increase of population, the development mode characterized by resource consumption exerts spatial stress on the agricultural development. The Loess Plateau of China ignored the protection of resources and environment, excessively pursued the rapid growth of economic indicators, and ignored the finiteness of ecological capacity and the fragility of environmental carrying capacity of the region. Only when the population was controlled within a certain range, and there was the consciousness of saving water and energy, and reducing the waste of resources, can there be a harmonious relationship between economy and resources.

Discussion and conclusion

From the perspective of supply and demand, the sustainable state of resources was evaluated, the coupling coordination degree model was used to measure the coupling coordination degree of urban resources in the Loess Plateau of China, and the

influencing factors of the coupling coordination degree of resources were revealed by using the method of geodetector. The analysis of the threshold effect of the factors influencing the coupling coordination degree of agricultural resources has important practical significance for alleviating the contradiction between economic growth and agricultural resources utilization and realizing regional high-quality development.

(1) Resource coupling coordination status. From 2000 to 2020, food supply in the Loess Plateau region was in surplus, and cities in short supply included Taiyuan, Lanzhou and Wuhai. Agricultural energy supply and demand were in different degrees of shortage, and Yuncheng was the city with the most serious shortage of agricultural energy. Only a few cities could meet the demand for agricultural water resources, including Tongchuan, Hainan Tibetan Autonomous Prefecture, Sanmenxia, Jiyuan, Huangnan Tibetan Autonomous Prefecture and Haidong City. The city with the most severe agricultural water shortage was Bayannur City. There are great differences in resource endowments in Loess Plateau region, so scientific and reasonable decisions should be made according to local conditions to make up for the shortage of resources. Focus on Yuncheng City, Bayannur city resource gap areas, so as to ensure the security of agricultural energy, agricultural water resources.

Compared with previous studies, the resource coupling coordination degree in the Loess Plateau region exhibits significant characteristics of spatial-temporal heterogeneity, and this conclusion is consistent with the research findings (Feng et al., 2020). Through further comparison with other typical regions in China, it is found that the Yangtze River Economic Belt also shows characteristics of spatial heterogeneity in terms of resource and environmental pressures (Liang et al., 2023). The above-mentioned studies jointly reveal that the spatial heterogeneity of regional resource conditions widely exists in different geographical units. Therefore, in-depth analysis of the characteristics of regional resource spatial heterogeneity is an important prerequisite for formulating sustainable development policies that are tailored to local conditions and differentiated, and it is of crucial significance for promoting regional coordinated development.

The measurement of regional agricultural resource coupling coordination degree provides theoretical guidance and decision support for the relevant management departments of resources and ecological environment to formulate regional resource coordination development strategies and countermeasures. From 2000 to 2020, the Loess Plateau region generally presented a state of coordinated development, among which Bayannur City, Yuncheng City and Taiyuan City were all in a state of imbalance and decline, which was manifested as insufficient supply of agricultural energy and water resources, and unbalanced supply and demand of food. Therefore, rational allocation of resources had become the key to regional sustainable development. It is recommended that resource management departments enhance comprehensive resource management and cross-departmental collaboration.

(2) Influencing factors of coupling coordination. Effective resource management requires not only a thorough understanding of the interaction between food, agri-energy and agri-water resources, but also the identification of the main influencing factors of agri-resource coupling. The total power of agricultural machinery, per capita GDP and resident population were the main factors affecting the coupling and coordination of resources. The interaction of all factors was greater than the single factor's influence on the coupling coordination degree of agricultural food, energy and water resources. The interaction enhancement relationship of factors was nonlinear enhancement, and the

interaction between per capita GDP and the general budget expenditure of local finance was the strongest.

This finding is highly consistent with the interpretation of the influencing factors of the coupling coordination degree in the previous research by Niu et al. (2021). In addition, the research on the Yangtze River Economic Belt also confirms that natural conditions and socio-economic factors, through complex interactions, jointly drive the high-quality development process of specific regions (Liang et al., 2022). Thus, it is evident that enhancing the coupling and coordination level of agricultural resources in the Loess Plateau region of China has become a key focal point. This not only helps to promote the construction of agricultural modernization and optimize the utilization efficiency of agricultural resources, but also effectively reduces resource waste and environmental pollution, laying a solid foundation for the sustainable development of the region.

Bivariate spatial autocorrelation analysis. In 2000 and 2020, the coupling coordination degree of total power of agricultural machinery and resources showed a high-high concentration of cooperation type city was Sanmenxia City. The spatial aggregation of per capita GDP and resource coupling coordination degree showed a high-high concentration of cooperation type city are Ordos City, Shizuishan City of Baotou City and Luoyang City. Inter-regional information exchange needs to strengthen the construction of Internet infrastructure and transportation infrastructure, reduce the cost of inter-regional flow of various factors, promote the frequent regional economic activities, and enhance the overall regional development benefits.

(3) Results of cross-sectional threshold model. We should not only pay attention to the direct influence of economic development on the coupling coordination degree of agricultural resources, but also pay attention to the influence of economic development on the coupling coordination degree of agricultural resources under the constraints of factors. The economic development level and resource coupling coordination degree in the Loess Plateau region showed an "inverted U-shaped" relationship, which increased first and then decreased, and there was a nonlinear relationship. When the total power of agricultural machinery was between 594,800 kW and 566,300 kW, the economic development level had the least negative effect on the coupling coordination degree of resources, showing a weak negative effect. When the permanent population ranged from 1,591,400 to 4,688,700, the coefficient of economic development level on the coupling coordination degree of resources was 0.331, and the economic development level had a positive effect on the coupling coordination degree of agricultural resources.

The results of this study reveal a significant threshold effect of economic development on the coupling coordination degree of agricultural resources: only within a reasonable range of factor inputs can economic development have a positive promoting effect on the coupling coordination degree of resources. This conclusion is highly consistent with the research findings at the provincial level in China (Qi et al., 2021; Wang et al., 2023). In addition, evidence from cross-scale studies further confirms the universality of this effect: studies at the urban scale (Wen et al., 2022) also indicate that the threshold effect of the coupling coordination degree of resources is prevalent in different geographical units.

The spatial distribution of resources in the Loess Plateau region is uneven, and agricultural production faces many difficulties and challenges. In order to alleviate the contradiction between regional economy and resource utilization, the agricultural sector should adopt a multi-pronged adaptation strategy, and promote the transformation of

economic growth from "quantity" to "quality" by formulating effective strategies of agricultural protection and development and utilization. In addition, all industries and departments also need to work together to promote resource sharing and coordinated development, from the aspects of technology, management, policies, etc., to help high-quality agricultural development, and promote the coordinated development between regional economy and resource utilization. In general, this research enriches the research findings in the Loess Plateau region from the perspective of resource supply and demand, offering a novel analytical framework for regional sustainable and high-quality development. A comprehensive evaluation of the current state of food, agricultural energy, and agricultural water resources in the Loess Plateau region is conducted. By elucidating the current status of agricultural resources and identifying spatial variations in regional resource availability, this study facilitates the formulation of targeted resource management strategies to ensure the security of regional agricultural resources, which holds practical significance for the achievement of high-quality regional development.

Author contributions. Jing Zhu: Writing–Original Draft, Resources, Methodology, Data curation, Conceptualization, Visualization. Qiujie Li: Writing – Original Draft, Visualization, Software, Methodology, Formal analysis, Data curation. Jie Luo: Writing – Review & Editing, Methodology, Formal analysis. Xinyuan Xie: Writing –Review & Editing.

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APPENDIX

Spatial trend surface

Suppose $Z_i(X_i, Y_i)$ represents the actual coupling coordination degree of food, agricultural energy and agricultural water resources, then the spatial trend surface $z_i(x_i, y_i)$ exists.

$$Z_i(X_i, Y_i) = z_i(x_i, y_i) + \varepsilon_i \quad (\text{Eq.1})$$

In *Formula (1)*, (x_i, y_i) is spatial coordinate; ε_i is the residual difference between the actual value and the trend value of resource coupling coordination degree.

Geodetector

The theoretical model is as follows.

$$q = 1 - \frac{\sum_{h=1}^L N_h \sigma_h^2}{N \sigma^2} \quad (\text{Eq.2})$$

In *Formula (2)*, $h = 1, \dots, L$ is the classification of dependent variables or factors; N_h and N are respectively the number of cities in each category h and the whole region of Loess Plateau of China. σ_h^2 and σ^2 are respectively the variances of the resource coupling coordination degree of class h and the whole region; q is the influence of the influence factor on the coordination degree of resource coupling, and the value range of q is $[0,1]$. The larger the value is, the stronger the explanatory power of the factor on the dependent variable is. The meaning of the q value is that the independent variable explains $(100 \times q)\%$ of the dependent variable. There are

five types of interactions, nonlinear attenuation, single-factor nonlinear attenuation, two-factor enhancement, mutual independence, and nonlinear enhancement.

Spatial autocorrelation model

Based on the Geoda spatial analysis tool, the local bivariate spatial correlation was calculated with the following formula (Gao et al., 2022).

$$I_{ab} = \frac{X_a^i - \overline{X_a}}{\sigma_a} \times \sum_{j=1}^n \left(w_{ij} \frac{X_b^j - \overline{X_b}}{\sigma_b} \right) \quad (\text{Eq.3})$$

In *Formula (3)*, I_{ab} is the local bivariate spatial autocorrelation index, X_a^i and X_b^j are the values of variable a of geographical unit i and variable b of geographical unit j respectively; $\overline{X_a}$ and $\overline{X_b}$ are the average values of attribute a and attribute b respectively; σ_a and σ_b are the variances of the attributes of a and b respectively; w_{ij} is the space weight matrix. Among them, I_{ab} forms four clustering patterns, and high-high and low-low clustering types represent the regions with high spatial correlation of high variable values and low variable values respectively, indicating that variables in adjacent regions were collaborative regions. The high-low and low-high clustering types respectively represent the regions with high spatial correlation of variable high-low value and variable low-high value, indicating that variables in adjacent regions are tradeoff regions. The non-significant region is independent.