Spatiotemporal Coupling and Coordination Relationship between Ecosystem Services and Water-Energy-Food System Security in Xinjiang: A Postprint

Authors: Celebration, Wenjie Wu, Wang Zhiqiang, Wang Tonghao

Date: 2026-01-30T16:53:17+00:00

Abstract

Water, energy, and food are fundamental resources supporting socio-economic development in arid regions, while ecosystem services are a crucial guarantee for maintaining the sustainable supply of these resources. Exploring the relationship between ecosystem services and the water-energy-food (WEF) system security in arid and semi-arid regions is of great significance for sustaining ecosystem health, promoting sustainable resource use, and achieving high-quality regional development. Based on land use, water consumption, and socio-economic data for Xinjiang from 2005 to 2023, this study employs the InVEST model, an accelerated genetic algorithm-projection pursuit model, and a coupling coordination degree model to quantify ecosystem services and WEF system security, analyze their coupling coordination degree, and, using the geographical detector, investigate the interaction mechanisms between the two systems. The results show that: (1) From 2005 to 2023, ecosystem services in Xinjiang remained overall stable, with distinct spatial differentiation patterns. Ecosystem services exhibit a diffusion trend from oasis areas toward surrounding regions. Water yield first increased, then decreased, and then rose again; habitat quality remained basically stable; carbon storage increased slowly; and soil conservation showed a fluctuating downward trend. The overall WEF system security in the study area exhibited an upward trend, gradually improving from an unsafe state to a basically safe state, with pronounced regional differences characterized by "higher in the north and lower in the south, with contiguous expansion of core areas." (2) The coupling coordination degree between ecosystem services and WEF system security displays an overall spatial pattern of "higher in the north and lower in the south." The coupling coordination degree improved from mild disorder to critical coordination, while the average annual growth rate gradually slowed. Water scarcity and spatial mismatch intensified structural contradictions in the synergistic development of the system, making it urgent to break development bottlenecks by improving resource use efficiency. (3) There is a significant interactive relationship between ecosystem services and WEF system security. River basins and precipitation are key factors through which ecosystem services affect WEF system security, whereas water resource utilization and food production are important factors through which WEF system security affects ecosystem services.

Full Text

Spatiotemporal Coupling and Coordination of Ecosystem Services and Water-Energy-Food System Security in Xinjiang

ZHU Qing, WU Wenjie, WANG Zhiqiang, WANG Tonghao (College of Public Administration (Law School), Xinjiang Agricultural University, Urumqi 830052, Xinjiang, China)

Abstract: Water, energy, and food are fundamental resources supporting socioeconomic development in arid regions, while ecosystem services are crucial for maintaining the sustainable supply of these resources. Investigating the relationship between ecosystem services and water-energy-food (WEF) system security in arid and semi-arid zones is essential for ecosystem health, sustainable resource utilization, and regional high-quality development. Based on land use, water consumption, and socioeconomic data from Xinjiang for the period 2005–2023, this study employs the InVEST model, accelerated genetic algorithm projection pursuit model, and coupling coordination degree model to quantify ecosystem services and WEF system security, analyze their coupling coordination degree, and explore the interaction mechanisms between the two systems using a geographic detector. The results indicate: (1) Ecosystem services in Xinjiang remained generally stable from 2005 to 2023, with pronounced spatial heterogeneity characterized by diffusion from oasis areas outward. Water yield first increased, then decreased, and then increased again. Habitat quality remained basically stable, carbon storage increased slowly, and soil retention showed a fluctuating downward trend. The overall security of the WEF system in the study area exhibited an upward trend, gradually improving from an unsafe state to a basically safe state, characterized by a spatial pattern of “high in the north, low in the south, with continuous expansion of core areas.” (2) The coupling coordination degree between ecosystem services and WEF system security displayed a “high in the north, low in the south” spatial pattern. The degree improved from mild disorder to marginal coordination, with the annual growth rate gradually slowing. Water resource scarcity and spatial mismatch have intensified structural contradictions in the synergistic development of the systems, necessitating urgent breakthroughs in development bottlenecks through improved resource utilization efficiency. (3) A significant interactive relationship exists between ecosystem services and WEF system security. Watershed and precipitation are key factors through which ecosystem services influence WEF system security, while water resource utilization and food production are important factors through which WEF system security affects ecosystem services.

Keywords: ecosystem services; WEF system security; coupling coordination; Xinjiang

Ecosystem services serve as a critical link between natural ecological and socioeconomic systems by providing ecological products and services such as water, carbon, soil, and biological populations, thereby supporting the production and sustainable utilization of water, energy, and food for society, which is of great significance for human survival and development [1-3]. Xinjiang, located in the arid and semi-arid region of northwestern China, features a fragile ecological environment and water resource shortages while simultaneously serving as a national strategic energy reserve base and an important grain-producing area. Consequently, the water-energy-food system faces multiple pressures, and the two systems have formed a special symbiotic relationship that requires a coupling coordination mechanism to balance ecological protection and resource development [4-6].

Research on ecosystem services both domestically and internationally has primarily focused on three aspects: first, revealing spatiotemporal evolution characteristics and influencing factors of ecosystem services through methods such as the InVEST model, geographically weighted regression, and geographic detectors combined with multi-source data [7-9]; second, predicting ecosystem service changes and restoration practices through multi-scenario simulations and robotic technologies such as remotely operated underwater vehicles, autonomous underwater vehicles, and crawling robots [10-11]; and third, investigating relationships between ecosystem services and other factors through coupling coordination correlation analysis and Pearson models [12-14]. Water-energy-food system research has mainly employed qualitative analysis, coupling coordination degree models, system dynamics models, and Durbin models to explore coupling coordination relationships, evolution characteristics, and influencing factors within the water-energy-food system [15-17]. Additionally, some scholars have studied ecosystem services from the DPSIR perspective to examine the synergistic and trade-off relationships among various internal elements of ecosystem services [18-20]. Regarding research on the relationship between ecosystem services and WEF systems, methods such as coupling coordination degree models, grey correlation analysis, regression analysis, and SD models have been used to construct WEF systems with ecosystem services as subsystems, exploring their internal coupling coordination relationships, while the interactive relationship between the two systems requires further enrichment [21-23].

Based on this context, this paper employs a coupling coordination degree model to analyze the relationship between ecosystem services and WEF system security, treating ecosystem services and WEF system security as two relatively independent systems for comprehensive consideration. The InVEST model is used to measure ecosystem services, and based on the nonlinear relationship within the water-energy-food system, an accelerated genetic algorithm projection pursuit model is applied to calculate WEF system security levels. The coupling coordination degree model is then used to analyze the interactive and coordinated development relationship between the two systems, and a geographic detector is employed to explore the interaction mechanism between systems, aiming to provide theoretical support for the efficient utilization of ecological resources and high-quality socioeconomic development in Xinjiang and to promote the coupled and coordinated development of regional socioeconomic development and ecosystem security in Xinjiang.

1.1 Study Area Overview

Xinjiang is located in the hinterland of the Eurasian continent and represents a typical arid region in China, featuring a "three mountains surrounding two basins" geomorphological pattern, with the Altai Mountains in the north, the Tianshan Mountains in the center, and the Kunlun-Altun Mountains in the south collectively embracing the Junggar and Tarim basins to form a closed natural geographical unit [Figure 1: see original paper]. As an important national strategic energy base, Xinjiang is rich in coal and oil and gas resources, with wind and solar energy development potential ranking among the highest in the country, and its oasis irrigation agriculture possesses unique advantages. In 2023, Xinjiang' s urban population density was 3.322×10^3 people $\cdot$ km^{-2}, the permanent resident urbanization rate was 59.24%, total grain output was 3.3493×10^7 t, per capita grain production was 415 kg $\cdot$ person^{-1}, natural gas production was 4.1727×10^9 m^3, and the proportions of primary, secondary, and tertiary industries were 14.3%, 40.3%, and 45.4%, respectively. The limited carrying capacity of oases concentrates the region' s main population and economic activities, creating prominent contradictions among water resource utilization, energy development, grain production, and ecological protection.

1.2 Data Sources and Processing

Land use data and watershed boundary data were obtained from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn). Elevation data were derived from the World Soil Database (https://data.tpdc.ac.cn/home). Precipitation and potential evapotranspiration data were sourced from the National Qinghai-Tibet Plateau Data Center (https://dataspace.copernicus.eu/). Soil data were obtained from the World Soil Database (https://data.tpdc.ac.cn/home). Socioeconomic and resource data were collected from the *Xinjiang Statistical Yearbook*, *Xinjiang Water Resources Bulletin*, *China Energy Statistics Yearbook*, *China Environmental Statistics Yearbook*, and *China Agricultural Statistics Yearbook*. Missing data were supplemented using interpolation methods. The study period spans from 2005 to 2023.

1.3.1 Ecosystem Service Measurement Methods

The InVEST model was employed to quantify four key ecosystem services: water yield (WY), habitat quality (HQ), carbon storage (CS), and soil retention (SDR). Specific calculation methods are detailed in reference [24]. The Integrated Ecosystem Service Index (ICES) was constructed from a holistic perspective to comprehensively evaluate Xinjiang' s ecological service level using a weighted average method. The calculation formula is as follows:

$$\mathrm{ICES}_j = \sum_{i=1}^{n} w_i S_{ij}$$

where ICES_j represents the integrated ecosystem service index for year j, with an index range of $[0, 1]$; a higher index indicates better ecosystem service level; n is the number of ecosystem service types; w_i is the weight of the i-th ecosystem service; and S_{ij} is the normalized value of the i-th ecosystem service in year j. Based on existing research [25] and considering the study area conditions, the weight for each ecosystem service was determined to be 0.25.

1.3.2 WEF System Security Measurement Methods

The accelerated genetic algorithm projection pursuit model was adopted to calculate WEF system security levels. This model combines projection pursuit with real-code accelerated genetic algorithms, making it suitable for addressing the nonlinear, dynamic, and high-dimensional characteristics of multi-system coupling and providing more scientific threshold identification and priority ranking [26]. Drawing on existing research [27], the system was divided into six subsystems: water resources, energy, food, water-energy, water-food, energy-food, and water-energy-food (Table 1) to construct a projection index function.

The projection pursuit model synthesizes p-dimensional data $\{x(i,j)|j = 1, 2, 3, \dots, p\}$ into one-dimensional projection values $z(i)$ along direction $a = \{a(1), a(2), a(3), \dots, a(p)\}$, constructing a projection index function based on the distribution characteristics of "small concentration and large dispersion" of projection values. The calculation formula is:

$$z(i) = \sum_{j=1}^{p} a(j)x(i,j), \quad i = 1, 2, 3, \dots, n$$

The projection index function is constructed as:

$$Q(a) = S_z D_z$$

where S_z is the standard deviation of projection values $z(i)$, and D_z is the local density of projection values $z(i)$:

$$S_z = \sqrt{\frac{\sum_{i=1}^{n}(z(i) - E(z))^2}{n-1}}$$

$$D_z = \sum_{i=1}^{n}\sum_{j=1}^{n}(R - r(i,j)) \cdot f(R - r(i,j))$$

$$r(i,j) = |z(i) - z(j)|$$

Here, $E(z)$ is the mean of sequence $z(i)(i = 1, 2, 3, \dots, n)$; R is the window radius of local density, determined experimentally; f is the unit step function, which equals 1 when $R - r(i,j) \geq 0$ and 0 otherwise; and $r(i,j)$ represents the distance between samples.

Since the projection index function $Q(a)$ varies only with the projection direction a, the optimal projection direction can be determined by maximizing the projection index function:

$$\text{Maximize objective function: } \max Q(a) = S_z|D_z|$$

$$\text{Constraint condition: } \sum_{j=1}^{p} a^2(j) = 1$$

For evaluation result classification, the optimal projection direction a is substituted into the formula. Using national data as the standard, the maximum or theoretical maximum value achievable by positive indicators during the study period is set as the upper limit for "very safe," while the minimum or theoretical minimum value serves as the lower limit for "very unsafe" [28]; the opposite applies to negative indicators. Five intervals are evenly divided between the upper and lower limits (Figure 2) and adjusted according to actual conditions. Larger projection values indicate higher levels and safer systems. System security is classified into five levels: very unsafe (Level 1), unsafe (Level 2), basically safe (Level 3), relatively safe (Level 4), and very safe (Level 5).

1.3.3 Coupling Coordination Degree Model

The coupling coordination degree model integrates multi-dimensional indicator systems to accurately reflect the nonlinear interactive relationship between ecosystem services and WEF system security, revealing the strength of interactions and coordination between systems [29]. The calculation formulas are as follows:

$$C = 2\frac{\sqrt{U_1 U_2}}{U_1 + U_2}$$

$$T = \alpha U_1 + \beta U_2$$

$$D = \sqrt{C \cdot T}$$

where C is the coupling degree; T is the coordination degree; U_1 and U_2 are the comprehensive values of ecosystem services and WEF system security, respectively; and α and β are the corresponding weights for ecosystem services and WEF system security, both set at 0.5. Based on relevant studies [30], the coupling coordination degree is classified into five types: highly disordered, mildly disordered, marginally coordinated, basically coordinated, and highly coordinated (Table 2).

1.3.4 Parameter Optimal Geographic Detector

The parameter optimal geographic detector automatically selects key parameters in the geographic detector model through data-driven or algorithmic optimization to obtain optimal q values [31]. The q value output from the factor detection model in the geographic detector is used to quantify the single-factor influence of Xinjiang' s ecosystem service indicators on WEF system security and to identify key influencing factors of WEF system security on ecosystem services [32]. The calculation formula is:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2}$$

where the q value represents the explanatory power of independent variables on dependent variables, ranging from $[0, 1]$, with larger values indicating stronger explanatory power; $h = 1, 2, 3, \ldots, L$ represents strata of the variable; N_h and N are the numbers of units in stratum h and the entire region, respectively; σ_h^2 and σ^2 are the variances of the dependent variable in stratum h and the entire region, respectively; and SSW and SST are the sum of within-stratum variance and total variance, respectively.

Explanatory power of dependent variables on independent variables varies across different spatial scales [33]. Considering the actual conditions of the study area, ten spatial scales were constructed (Table 3), and the 90th percentile of q values of driving factors was calculated and compared [34]. The results showed that a 70 km grid better reflects the influence of driving factors on dependent variables.

2.1.1 Spatiotemporal Distribution Characteristics of Ecosystem Services

From 2005 to 2023, ecosystem services in Xinjiang exhibited a binary differentiation characteristic of “mountain-basin” patterns (Figure 3), influenced by both natural conditions and human interventions. High-value areas were concentrated near the Tianshan, Kunlun, and Altai mountains and in the Ili River basin, while low-value areas were mainly distributed in the hinterlands of the Tarim and Junggar basins. During the study period, various ecosystem services showed different changing trends. Water yield first increased, then decreased, and then increased again, with average annual water yield decreasing from 44.42 mm to 40.76 mm. Habitat quality remained basically stable, maintained at 0.30-0.31. Carbon storage showed a slow increasing trend, rising from 1.7502×10^7 t to 4.688×10^7 t, an increase of 1.30%. Soil retention showed a fluctuating downward trend, decreasing from 4.378×10^7 t to 1.938×10^7 t.

2.1.2 Spatiotemporal Changes in Integrated Ecosystem Services

The integrated level of ecosystem services in Xinjiang showed a spatial differentiation pattern of “low in the center, high at the edges” (Figure 4). The overall level of integrated ecosystem services was relatively low and basically stable, with ICES values of 0.34, 0.35, 0.36, 0.37, and 0.38 for 2005, 2010, 2015, 2020, and 2023, respectively. In 2005, significant changes occurred in the Ili River valley, Altai Mountains, and Kunlun Mountains in northern Xinjiang, where ecosystem services expanded from high-level areas to low-level areas. By 2010, the overall spatial distribution became relatively stable. Constrained by natural geographical factors, the Tarim Basin and the desert hinterland of southern Xinjiang remained in low-value areas for extended periods, while the Ili River valley and the southern foothills of the Altai Mountains in northern Xinjiang formed core water conservation areas relying on mountain precipitation and glacier meltwater, which, combined with protection zone policies, created high-value areas.

2.2 Spatiotemporal Evolution of WEF System Security in Xinjiang

The overall security of Xinjiang’ s WEF system showed a fluctuating upward trend (Figure 5), gradually improving from an initially unsafe state to a basically safe state. In 2005, the WEF system security evaluation level was generally low. According to Xinjiang’ s 2005 Water Resources Bulletin, severe drought and flood disasters in 2005 damaged the WEF system, causing security levels to decline. By 2010, comprehensive management continued to deepen, and WEF system security gradually improved. By the end of 2015, the comprehensive implementation of the river and lake chief system, along with in-depth promotion of targeted poverty alleviation and ecological protection, led to rapid improvement in WEF system security. Additionally, Xinjiang’ s WEF system security level exhibited a spatial characteristic of “high in the north, low in the south, with continuous expansion of core areas” (Figure 6). In 2005, Kashgar, Aksu, Bayingolin, Hami, and Bortala were upgraded to unsafe, while Tacheng and Changji were upgraded to basically safe. In 2010, Ili was upgraded to basically safe, and other regions escaped the very unsafe state, with the entire region entering an unsafe state spatially. In 2015, WEF system security levels improved significantly, with Kashgar, Aksu, Bayingolin, and Altay upgraded to basically safe. By 2020, WEF system security levels further improved, with unsafe, basically safe, and relatively safe conditions coexisting across the region, and spatial differences further expanded.

2.3.1 Temporal Changes in Coupling Coordination Degree

From 2005 to 2023, the coupling coordination degree between ecosystem services and WEF system security in Xinjiang showed an overall upward trend (Figure 7), improving from mild disorder to marginal coordination at a relatively fast growth rate. The coupling coordination degrees for 2005-2010, 2010-2015, and 2015-2020 were 1.85%, 0.86%, and 0.34%, respectively, with average annual growth rates of 0.37%, 0.17%, and 0.07%, respectively. The system remains in the marginal coordination stage, with the growth rate gradually slowing. The coupling coordination degree has encountered a development bottleneck, requiring breakthrough pathways through synergistic optimization of key elements.

2.3.2 Spatial Evolution Analysis of Coupling Coordination Degree

The coupling coordination degree between ecosystem services and WEF system security in various regions of Xinjiang showed an upward trend with significant regional differences (Figure 8), displaying a distribution pattern of high in the north and low in the south. In 2005, the overall coupling coordination level was low. The Ili River valley in northern Xinjiang, relying on stable runoff and precipitation, 率先 formed a basically coordinated area, while the Tarim Basin in southern Xinjiang, affected by closed topography and shortage of ecological water, experienced large-scale high disorder. In 2010, the Tarim River ecological water conveyance project in southern Xinjiang effectively improved coordination levels, significantly reducing high-disorder areas in southern Xinjiang. By 2015, basically coordinated areas in northern Xinjiang expanded toward the Junggar Basin, improving overall regional coupling coordination. In 2020, basically coordinated areas further extended eastward, with most areas of the Tarim Basin upgraded to marginal coordination and disorder areas becoming more dispersed. In 2023, mildly disordered areas were fragmented, highly coordinated patches increased, and the coupling coordination degree across Xinjiang further improved. Areas in western Kunlun and parts of the Junggar Basin were upgraded to marginal coordination, disorder areas showed point distributions, and highly coordinated areas in the Ili River basin shifted from point to belt distributions.

2.3.3 Spatiotemporal Evolution of Coupling Coordination Degree by Prefecture

Using 0.5 as the threshold to divide disorder and coordination intervals [35], Xinjiang’ s prefectures and regions were classified into three types based on their coupling coordination degree levels and growth trends: steady coordination development type, rapid coordination improvement type, and disorder transformation and 攻坚 type. The steady coordination development type includes Ili, Changji, and Tacheng, which have effectively established long-term synergistic mechanisms between ecosystem services and WEF system security through technological innovation and efficient resource utilization, forming a positive development trend. The rapid coordination improvement type covers Altay, Kashgar, Aksu, Bortala, Kizilsu, and Urumqi. Altay achieved rapid growth in regional coupling coordination through ecological projects such as returning grazing land to grassland. Urumqi experienced excessive industrial water use and increased dependence on traditional energy due to rapid urban expansion, but later saw fluctuating recovery in coordination through optimization of industrial water-saving standards, water supply network renovation, and increased clean energy consumption. Aksu and Kizilsu broke through the marginal threshold by vigorously developing water-saving agriculture in irrigation districts. The disorder transformation and 攻坚 type involves extensive regions exhibiting dual constraints of resource and industrial path dependence. Hotan suffers from persistently low coordination due to extreme arid climate constraints, uneven seasonal runoff distribution, and prominent water supply-demand contradictions. Karamay shows low overall coupling coordination levels constrained by oil industry chain path dependence. Hami and Turpan face prominent water resource tension due to excessively high agricultural water use proportions, restricting further development of coupling coordination. Bayingolin’ s oil and gas development conflicts with ecological protection, constraining further improvement in coupling coordination.

2.4 Interaction Mechanism Analysis

Using the factor detection method of the geographic detector and selecting natural elements including land use type, watershed, elevation, precipitation, potential evapotranspiration, and soil erosion, we identified key influencing factors of ecosystem services on the spatial differentiation of WEF system security (Figure 9). Potential evapotranspiration and soil erosion only showed significant impacts in some years, while watershed and precipitation were the dominant long-term factors affecting WEF system security. As an important carrier of water resources, watershed showed the strongest explanatory power for WEF system security, with q values of 0.45, 0.42, 0.40, 0.38, and 0.35 from 2005 to 2023. Water resource elements play a decisive role in WEF system security in arid regions, necessitating the establishment of an ecosystem management model based on water resource carrying capacity and making watershed-scale water resource regulation a key component of WEF security pattern construction.

For variables passing significance tests, *q* mean values were calculated (Figure 10) to identify key influencing factors of WEF system security on ecosystem services, which were, in order, per capita water resources (0.42), total grain output (0.38), water resource development utilization rate (0.35), grain yield per unit area (0.33), and total agricultural machinery power (0.31). Compared with energy development, water resource utilization and agricultural production have stronger impacts on ecosystem services. Additionally, after 2015, *q* values of various factors shifted from violent fluctuations to gentle trends, with the explanatory power of single factors on ecosystem services generally weakening and the combined effect of multiple elements gradually becoming dominant.

3 Discussion

Various components of ecosystems interact and influence each other, acting on the same or different ecosystem services [36]. In the study area, changes in forest, cultivated land, and grassland areas directly affect ecological source integrity and service synergy by regulating vegetation canopy density and root consolidation depth [37]. The forest ecosystem in the study area demonstrates significant carbon sequestration capacity, with abundant carbon storage in the Ili River basin, Junggar Basin, and marginal areas, consistent with carbon storage trends predicted by Yang et al. [38]. Water yield exhibits typical climate-driven characteristics, with high precipitation and low potential evapotranspiration in the Ili River basin of Xinjiang jointly supporting high water yield, a result that aligns with long-term observational data from Chen et al. [39]. The synergistic improvement of high habitat quality and soil retention capacity in the Ili River valley demonstrates vegetation’ s soil consolidation ability [40], verifying the spatial coupling pattern between biodiversity and service functions proposed by Zhang et al. [41].

4.1 Conclusions

(1) From 2005 to 2023, ecosystem services in Xinjiang remained generally stable, with obvious spatial differentiation characteristics showing diffusion from oasis areas outward. Water yield first increased, then decreased, and then increased again. Habitat quality remained basically stable, carbon storage increased slowly, and soil retention showed a fluctuating downward trend. The overall security of the WEF system in the study area exhibited an upward trend, gradually improving from an unsafe state to a basically safe state, presenting a spatial characteristic of “high in the north, low in the south, with continuous expansion of core areas.”

(2) From 2005 to 2023, the coupling coordination degree between ecosystem services and WEF system security displayed a “high in the north, low in the south” distribution pattern. The degree improved from mild disorder to marginal coordination, with the annual growth rate gradually slowing.

Water resource scarcity and spatial mismatch have intensified structural contradictions in the synergistic development of the systems, necessitating urgent breakthroughs in development bottlenecks through improved resource utilization efficiency.

(3) A significant interactive relationship exists between ecosystem services and WEF system security. Watershed and precipitation are key factors through which ecosystem services influence WEF system security, while water resource utilization and food production are important factors through which WEF system security affects ecosystem services.

4.2 Recommendations

Xinjiang has vast territory, rich ecosystem diversity, and complex interwoven issues of urban development, industry, energy, and ecology. Effective synergy must be formed across conceptual, technical, policy, and management levels to flexibly adapt to ecosystem thresholds in arid zones and scientifically realize resource and environmental values. (1) Protect green ecological barrier functions and improve resource utilization efficiency. Strengthen protection of high carbon storage areas such as the Ili River basin and marginal oases of the Junggar Basin, limit development intensity, and promote vegetation restoration in forests and grasslands. In ecologically fragile areas of southern Xinjiang, promote salinization control and sand fixation projects to enhance water conservation and soil retention capacity and curb degradation of ecosystem service functions. (2) Promote industrial optimization and transformation and strengthen regional collaborative governance. Based on resource endowments and location advantages, deepen opening-up cooperation and scientific and technological innovation to promote the integration of traditional industry upgrading and emerging business forms. (3) Improve ecological environment zoning and strengthen dynamic regulation. Emphasize watershed-scale water resource management and control, strengthen regional cooperation, coordinate water-energy-food system interactions, optimize spatial suitability of resource utilization, implement systematic management of mountains, rivers, forests, farmlands, lakes, grasslands, and deserts, scientifically delineate ecological environment zones, establish risk warning threshold response mechanisms, achieve hierarchical response and dynamic regulation, and improve the precision and adaptability of spatial governance.

References

[1] Ding Tonghui, Chen Junfei, Ji Juan, et al. Research progress and prospect of the coupling between water-energy-food nexus and ecosystem services[J]. Acta Ecologica Sinica, 2025, 45(6): 1-14.

[2] Zhang Xiaoyan, Ma Weiyan, He Weijun, et al. Spatial and temporal evolution characteristics and influencing factors of ecosystem services in the Three Gorges Ecological Economic Corridor of the Yangtze River[J]. Ecological Economy, 2023, 39(8): 145-155.

[3] Aguzzi J, Thomsen L, Flögel S, et al. New technologies for monitoring and upscaling marine ecosystem restoration in deep sea environments[J]. Engineering, 2024, 34(3): 195-211.

[4] Qi B, Yu M, Li Y. Multi scenario prediction of land use changes and ecosystem service values in the Lhasa River Basin based on the FLUS-Markov model[J]. Land, 2024, 13(5): 597.

[5] Wang Daoyuan, Wang Jin, Liu Huifang, et al. Research on coupling coordination and driving factors of ecosystem services and economic development in Shanxi Province[J]. Areal Research and Development, 2024, 43(6): 52-59.

[6] Li Chengyu, Zhang Shiqiang. Chinese provincial water-energy-food coupling coordination degree and influencing factors research[J]. China Population, Resources and Environment, 2020, 30(1): 120-128.

[7] Hao Yijia, Xia Yong, Zhang Yang, et al. Research and forecast analysis on the coupling coordinated development of water-energy-food system in Northwest China[J]. Research of Soil and Water Conservation, 2025, 32(3): 251-259, 269.

[8] Tan Hanze, Zhang Zezhong, Feng Kai, et al. Coordination and driving mechanism of water-energy-ecology coupling system in Inner Mongolia Reaches of Yellow River based on coupling coordination degree model[J]. Pearl River, 2025, 46(4): 101-112.

[9] Zhang Ziqing. Study on Coordinated Development of the Water-Energy-Food Nexus System and Its Influencing Factors in Henan Province[D]. Zhengzhou: Henan University of Finance and Economics, 2024.

[10] Li Huiqiang, Liang Xiaoying, Wei Zheng, et al. Driving force analysis of ecosystem service bundle change based on logistic regression model: A case study of Guanzhong Economic Zone[J]. Ecology and Environmental Sciences, 2024, 33(11): 1803-1815.

[11] Li Bingkun, Zhang Xiaoke, Luo Zhanbin, et al. Matching between supply and demand of ecosystem services based on the water-energy-food nexus: A case of the urban agglomeration on the northern slope of Tianshan Mountains[J]. Arid Land Geography, 2025, 48(4): 571-585.

[12] Yang Shunfa, Zan Mei, Yuan Ruilian, et al. Carbon stock changes and forecasting in Xinjiang based on PLUS and InVEST model approach[J]. Environmental Science, 2025, 46(1): 378-387.

[13] Teng Lun, Zhang Feiyun, Li Qian, et al. Investigation of the interplay and coordination relationship between ecosystem services and water use efficiency in Xinjiang[J]. China Environmental Science, 2025, 45(3): 1556-1567.

[14] Liu Xiaoyu, Wu Wei, Yang Chengjun. Spatiotemporal variation and driving factors of ecosystem services in Dawen River Basin[J]. Journal of Hydroecology, 2025, 46(1): 189-202.

[15] Wang Yubao, Pulong, et al. Comprehensive evaluation of water-energy-food nexus safety in Xinjiang[J]. Journal of Agricultural Machinery, 2020, 51(6): 264-272.

[16] Li Yuting, Wang Yihan, Liu Zimin. Research on the coupling coordination degree of Chinese cities water-energy-food nexus system and influencing factors[J]. Journal of Industrial Technological Economics, 2023, 42(6): 97-105.

[17] Chen Guangzhou, Wang Jiaquan. Health assessment of urban ecosystem based on a projection pursuit model[J]. Acta Ecologica Sinica, 2009, 29(9): 4918-4923.

[18] Fan Dongjun, Ke Han, Cao Runmin. Modification and improvement of coupling coordination degree model[J]. Statistics & Decision, 2024, 40(22): 41-46.

[19] Dong Pengbei, Ren Zongping, Li Peng, et al. Ecosystem services trade-offs and synergies driven by land use changes in Ningxia[J]. Arid Zone Research, 2024, 41(6): 1032-1044.

[20] Zhang Wenrui, Sun Dongyuan, Wang Yike, et al. Coupling relationship and spatio-temporal differentiation of the water resources-ecological environment-social economic system in the Hexi Corridor[J]. Arid Zone Research, 2024, 41(9): 1527-1537.

[21] Li Y, Liu W, Feng Q, et al. The role of land use change in affecting ecosystem services and the ecological security pattern of the Hexi Regions, Northwest China[J]. Science of the Total Environment, 2023, 855: 158940.

[22] Chen Wudi, Liu Xiaohuang, Li Hongyu, et al. Spatiotemporal changes and driving factors of water yield service in Xinjiang from 1990 to 2018 based on InVEST model[J]. Geoscience, 2024, 38(3): 636-647.

[23] Wang Lan, Li Xiaojuan, He Jijun, et al. Spatiotemporal changes and influencing factors of soil conservation capacity in Linyi City of Shandong Province based on InVEST model[J]. Bulletin of Soil and Water Conservation, 2025, 45(1): 337-345, 356.

[24] Zhang Zhiru, Wan Huawei, Wang Yongcai, et al. Research on the relationship between biodiversity and ecosystem services in Xinjiang[J]. Environmental Monitoring and Forewarning, 2024, 16(5): 146-156.

[25] Chen W Z, Wang L X, Guo C X. Synergistic regulation of water-saving cultivation and dryland farming and its sustainable development pathways[J]. Geographical Research Bulletin, 2024, 3: 416-425.

[26] Sharafi S, Marzban Z, Dragovich D. Ecosystem service values and wheat agroecosystem management types in a semi-arid region, Iran[J]. Land, 2025, 14(4): 865.

[27] Song Y, Wang J, Ge Y, et al. An optimal parameters based geographical detector model enhances geographic characteristics of explanatory variables

for spatial heterogeneity analysis: Cases with different types of spatial data[J]. GIScience & Remote Sensing, 2020, 57(5): 593-610.

[28] Hou Caixia, Zhang Yuzhou, Yang Jianping. Analysis of the coupling coordination and obstacle factors of water-society system in the Guanzhong Plain urban agglomeration[J]. Arid Land Geography, 2025, 48(4): 717-727.

[29] Wang Jinfeng, Xu Chengdong. Geodetector: Principle and prospective[J]. Acta Geographica Sinica, 2017, 72(1): 116-134.

[30] Wu Xu, Zhang Xin, Ni Jianwei, et al. Analysis on the spatiotemporal coupling coordinated relationship between common prosperity and low carbon development in cities: A case study of the Yangtze River Delta Urban Agglomeration[J]. Ecological Economy, 2025, 41(7): 211-221.

[31] Shi Zhiyong, Xie Huili, Wang Zhenfeng, et al. Analysis of spatiotemporal heterogeneity of habitat quality and their driving factors based on optimal parameters based geographic detector for Fuzhou City, China[J]. Journal of Environmental Engineering Technology, 2023, 13(5): 1921-1930.

[32] Li Yan, Wu Hao, Zhu Lianqi, et al. Identification of ecosystem service degradation risks in Zhengzhou based on multi scenario simulation of land use changes[J]. Journal of Natural Resources, 2025, 40(2): 493-513.

[33] Zheng, et al. Driving force analysis of ecosystem service bundle change based on logistic regression model: A case study of Guanzhong Economic Zone[J]. Ecology and Environmental Sciences, 2024, 33(11): 1803-1815.

[34] Li Xiaojian, Ma Linbin. Characteristics and influencing factors of farmland conversion to non-agricultural uses in northeast Guangdong Province based on optimal parameter geographic detector[J]. Bulletin of Soil and Water Conservation, 2024, 44(5): 100-112.

[35] Li Y, Liu W, Feng Q, et al. The role of land use change in affecting ecosystem services and the ecological security pattern of the Hexi Regions, Northwest China[J]. Science of the Total Environment, 2023, 855: 158940.

[36] Chen Wudi, Liu Xiaohuang, Li Hongyu, et al. Spatiotemporal changes and driving factors of water yield service in Xinjiang from 1990 to 2018 based on InVEST model[J]. Geoscience, 2024, 38(3): 636-647.

[37] Wang Lan, Li Xiaojuan, He Jijun, et al. Spatiotemporal changes and influencing factors of soil conservation capacity in Linyi City of Shandong Province based on InVEST model[J]. Bulletin of Soil and Water Conservation, 2025, 45(1): 337-345, 356.

[38] Zhang Zhiru, Wan Huawei, Wang Yongcai, et al. Research on the relationship between biodiversity and ecosystem services in Xinjiang[J]. Environmental Monitoring and Forewarning, 2024, 16(5): 146-156.

[39] Chen W Z, Wang L X, Guo C X. Synergistic regulation of water-saving cultivation and dryland farming and its sustainable development pathways[J].

Geographical Research Bulletin, 2024, 3: 416-425.

[40] Sharafi S, Marzban Z, Dragovich D. Ecosystem service values and wheat agroecosystem management types in a semi-arid region, Iran[J]. Land, 2025, 14(4): 865.

[41] Song Y, Wang J, Ge Y, et al. An optimal parameters based geographical detector model enhances geographic characteristics of explanatory variables for spatial heterogeneity analysis: Cases with different types of spatial data[J]. GIScience & Remote Sensing, 2020, 57(5): 593-610.

Note: Figure translations are in progress. See original paper for figures.