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

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Abstract

Water, energy, and food are fundamental resources supporting socioeconomic development in arid regions, while ecosystem services are an important 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 maintaining ecosystem health, ensuring sustainable resource utilization, and promoting high-quality regional development. Based on land use, water consumption, and socioeconomic data for Xinjiang from 2005 to 2023, this study applies the InVEST model, an accelerated genetic algorithm-projection pursuit model, and a coupling coordination degree model to measure ecosystem services and WEF system security, analyze their coupling coordination degree, and investigate the interaction mechanisms between the systems using a geographical detector. The results show that: (1) From 2005 to 2023, ecosystem services in Xinjiang remained overall stable, with distinct spatial heterogeneity. Ecosystem services exhibit a diffusion pattern spreading outward from oasis areas; water yield first increased, then decreased, and then increased again; habitat quality remained basically stable; carbon storage increased slowly; and soil conservation showed a fluctuating downward trend. The overall security level of the WEF system in the study area displayed an upward trend, gradually improving from an insecure state to a basically secure state, with pronounced regional differences characterized by "higher in the north and lower in the south, with contiguous expansion in core areas." (2) The coupling coordination degree between ecosystem services and WEF system security exhibits 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 annual growth rate gradually slowed. The shortage and spatial mismatch of water resources have exacerbated 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 the 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 influences ecosystem services.

Full Text

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

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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 vital for ecosystem health, sustainable resource utilization, and regional high-quality development. Based on land use, water consumption, and socioeconomic data from Xinjiang spanning 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, and explore intersystem interaction mechanisms using geographic detector analysis. 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 exhibited a pattern of initial increase, subsequent decrease, and final increase; habitat quality remained essentially stable; carbon storage increased gradually; and soil retention showed a fluctuating downward trend. (2) Overall WEF system security demonstrated an upward trend, transitioning from an unsafe state to a basically safe state, with a spatial pattern of "high in the north, low in the south, and contiguous expansion of core areas." (3) The coupling coordination degree between ecosystem services and WEF system security displayed a "high in the north, low in the south" distribution pattern, progressing from mild disorder to critical coordination with a gradually slowing annual growth rate. Water scarcity and spatial misallocation have intensified structural contradictions in synergistic system development, necessitating breakthroughs through improved resource utilization efficiency. (4) 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

1. Introduction

Ecosystem services function as a critical link between natural ecological and socioeconomic systems by providing water, carbon, soil, and biological resources that support water, energy, and food production and sustainable utilization, which are essential for human survival and development. Xinjiang, located in the arid and semi-arid northwestern region of China, features fragile ecological environments and scarce water resources while serving as a national strategic energy reserve base and important grain-producing area. The WEF system faces multiple pressures, and the two systems have formed a special symbiotic relationship that requires coupling coordination mechanisms to balance ecological protection and resource development.

Domestic and international research on ecosystem services primarily focuses on three aspects: First, using models such as InVEST, geographically weighted regression, and geographic detectors combined with multi-source data to reveal spatiotemporal evolution characteristics and influencing factors of ecosystem services. Second, employing multi-scenario simulations and robotic technologies (e.g., remotely operated underwater vehicles, autonomous underwater vehicles, and crawling robots) to predict ecosystem service changes and restoration practices. Third, using coupling coordination analysis, Pearson correlation analysis, and regression models to investigate relationships between ecosystem services and other factors.

WEF system research primarily employs qualitative analysis, coupling coordination degree models, system dynamics models, and Durbin models to explore coupling coordination degrees and influencing factors within WEF systems. In studies on the relationship between ecosystem services and WEF systems, coupling coordination degree models, gray relational analysis, and regression analysis are commonly used to examine internal coupling coordination relationships, evolution characteristics, and influencing factors. Some scholars have also studied ecosystem services from the DPSIR perspective, exploring synergistic and trade-off relationships among various ecosystem service elements.

In summary, most studies focus on either ecosystem services or WEF system security as separate systems. Research on the relationship between ecosystem services and WEF system security remains limited. Some scholars have studied the ecosystem-WEF system relationship, but most treat the ecosystem as a subsystem within the WEF framework to explore internal coupling coordination, leaving the interactive relationship between the two systems to be further elucidated. Based on this, our study employs a coupling coordination degree model to analyze the relationship between ecosystem services and WEF system security, treating them as two relatively independent systems. We use the InVEST model to measure ecosystem services and apply an accelerated genetic algorithm projection pursuit model based on the nonlinear relationship between water and energy systems to measure WEF system security. We then use the coupling coordination degree model to analyze their interactive and coordinated development relationship and employ geographic detector analysis to explore the intersystem interaction mechanism. This research aims to provide theoretical support for efficient ecological resource utilization and high-quality socioeconomic development in Xinjiang, promoting the coupled and coordinated development of regional socioeconomic and ecosystem security.

1.1 Study Area Overview

Xinjiang is located in the hinterland of the Eurasian continent and represents a typical arid region in China. Its landform pattern features "three mountains sandwiching two basins," with the northern Altai Mountains, central Tianshan Mountains, and southern Kunlun-Altun Mountains enclosing the Junggar and Tarim basins to form a closed natural geographic unit. As an important national energy strategic 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. Green development has unique advantages in oasis irrigation agriculture. In 2023, Xinjiang' s permanent population was 3.3493\$$\times 10^{\{7\}, withanurbanizationrateof 59.24\times 10}$\{7\}\$ tons, and per capita GDP was 44,200 yuan/person. Natural gas production was 2.1192\$×10ˆ{10}\$ m^3. 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 between resource utilization, energy development, food production, and ecological protection.

1.2 Data Sources and Processing

Land use data and watershed boundary data were obtained from the Chinese Academy of Sciences Resource and Environmental Science Data Center (https://www.resdc.cn). Elevation data were sourced from the World Soil Database (https://dataspace.copernicus.eu/). Precipitation and potential evapotranspiration data were obtained from the National Tibetan Plateau Data Center (https://data.tpdc.ac.cn/home). Soil data were derived from the Harmonized World Soil Database. Socioeconomic 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 2005-2023.

Note: The base map was produced using the standard map from the National Geographic Information Public Service Platform (Map Review

No. GS(2024)0650), with no modifications to boundary lines. The same applies below.

[Figure 1: see original paper] Schematic diagram of the study area

1.3 Methodology

1.3.1 Ecosystem Services Measurement Methods We used the InVEST model to quantify four key ecosystem services: habitat quality (HQ), carbon storage (CS), sediment retention (SDR), and water yield (WY). Specific calculation methods are detailed in the literature. The Integrated Comprehensive Ecosystem Services (ICES) index was constructed using a weighted average approach to comprehensively assess Xinjiang' s ecosystem service level from a holistic perspective:

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

where ICES_j represents the integrated ecosystem service index for year j (larger values indicate higher ecosystem service levels), n is the number of ecosystem service types, w_i is the weight of ecosystem service i, and S_{ij} is the normalized value of ecosystem service i in year j. Based on existing research and considering the study area' s conditions, all ecosystem service weights were set to 0.25.

1.3.2 WEF System Security Measurement Methods We employed an accelerated genetic algorithm projection pursuit model, which combines projection pursuit with real-coded accelerated genetic algorithms and is suitable for solving nonlinear, dynamic, and high-dimensional coupling characteristics of multi-systems, providing more scientific threshold identification and priority ranking.

Indicator System Construction: Drawing on existing research, we established an indicator system comprising six subsystems: water resources, energy, food, water-food, water-energy, and energy-food (Table 1).

Projection Index Function Construction: 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 $a = \{a(1), a(2), a(3), \dots, a(p)\}$:

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

The projection index function $Q(a)$ is constructed according to the distribution characteristics of "small concentration, large dispersion" :

$$Q(a) = S_z \cdot D_z$$

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

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

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

where $E(z)$ is the mean of sequence $\{z(i)|i = 1, 2, 3, \dots, n\}$; R is the window radius for local density, determined experimentally; $r(i,j)$ represents the distance between samples; and $u(t)$ is a unit step function (value is 1 when $t \geq 0$, and 0 otherwise).

Projection Index Function Optimization: Since the projection index function $Q(a)$ changes only with projection direction a, the optimal projection direction can be determined by maximizing $Q(a)$:

$$\text{Maximize: } Q(a) = S_z \cdot D_z$$

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

Evaluation Result Classification: Using national data as the standard, the maximum or theoretical maximum value achievable by positive indicators in the study period was set as the upper limit for "very safe," while the minimum or theoretical minimum value served as the lower limit for "very unsafe" (inverse for negative indicators). The range between upper and lower limits was divided into five intervals (Figure 2), with adjustments made according to actual conditions. Larger projection values indicate higher grades and greater system security. Security levels were classified as: very unsafe (Level 1), unsafe (Level 2), basically safe (Level 3), comparatively safe (Level 4), and very safe (Level 5).

WEF system security indicator system

1.3.3 Coupling Coordination Degree Model The coupling coordination degree model integrates multi-dimensional indicator systems to accurately reflect nonlinear interactions between ecosystem services and WEF system security, revealing the strength of intersystem interactions and coordination:

$$C = 2\sqrt{\frac{U_1 \cdot U_2}{(U_1 + U_2)^2}}$$

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

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

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 weights of ecosystem services and WEF system security (both set to 0.5). Based on relevant research, coupling coordination degrees were classified into five types: severe disorder, mild disorder, critical coordination, basic coordination, and high coordination (Table 2).

Classification of coupling coordination degree types

1.3.4 Parameter-Optimal Geographic Detector (OPGD) 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. We used the factor detection model in OPGD to quantify the influence of individual ecosystem service indicators on WEF system security in Xinjiang and identify key influencing factors of WEF system security on ecosystem services:

$$q = 1 - \frac{\sum_{i=1}^{L} N_i \sigma_i^2}{N\sigma^2} = 1 - \frac{SSW}{SST}$$

where q represents the explanatory power of the independent variable on the dependent variable (range $[0, 1]$; larger q values indicate stronger explanatory power). L is the stratification of the independent variable; N_i and N are the number of units in layer i and the entire region, respectively; σ_i^2 and σ^2 are the variances of the dependent variable in layer i and the entire region, respectively; and SSW and SST are the sum of within-layer variances and total regional variance, respectively.

The explanatory power of dependent variables on independent variables varies across different spatial scales. We constructed evaluation units at 10 scales from 10 km to 100 km (Table 3), calculated and compared the 90th percentile of q values for driving factors. Results showed that 70 km grid cells better reflected the influence of driving factors on dependent variables.

90th percentile at different spatial scales

2. Results

2.1 Spatiotemporal Characteristics of Ecosystem Services

2.1.1 Spatiotemporal Distribution of Individual Ecosystem Services

From 2005 to 2023, Xinjiang’ s ecosystem services exhibited a binary differentiation pattern of “mountain-basin” (Figure 3), influenced by both natural conditions and human intervention. 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, individual ecosystem services showed different trends: water yield first increased, then decreased, and increased again, with average values of 37.26 mm, 44.42 mm, and 40.76 mm for 2005, 2014, and 2023, respectively. Habitat quality remained basically stable at 0.30–0.31. Carbon storage showed a slow increasing trend, rising from 1.7502×10^{9} t to 1.938×10^{9} t, an increase of 10.73%. Soil retention showed a fluctuating downward trend, decreasing from 2.720×10^{8} t to 1.846×10^{8} t. The spatial distribution of soil retention showed an upward trend in some areas on the northern slope of the Tianshan Mountains, Altai Mountains, Kunlun Mountains, and parts of the Ili River Valley.

2.1.2 Spatiotemporal Changes in Integrated Ecosystem Services The integrated ecosystem service level in Xinjiang showed a spatial differentiation pattern of “low in the center, high on the edges” (Figure 4). The overall level of integrated ecosystem services was relatively low and basically stable, with ICES means of 0.34, 0.35, and 0.35 for 2005, 2014, and 2023, respectively. In 2005, significant changes occurred in the Ili River Valley, Altai Mountains, and Kunlun Mountain areas in northern Xinjiang, where ecosystem services expanded from higher-level to lower-level areas. In 2014, the overall spatial distribution was relatively stable. By 2023, the spatial distribution pattern was essentially established. Constrained by natural geographic factors, the Tarim Basin and southern Xinjiang desert hinterlands experienced long-term drought, scarce surface runoff, and remained low-value areas. The Ili River Valley in northern Xinjiang and the southern foothills of the Altai Mountains formed water conservation core areas relying on mountain precipitation and glacier meltwater, which, combined with protected area policies, formed high-value areas.

2.2 Spatiotemporal Evolution of WEF System Security in Xinjiang

Overall, WEF system security in Xinjiang showed a fluctuating upward trend (Figure 5), gradually improving from an initial unsafe state to a basically safe state. The security level continued to improve. According to the *Xinjiang Water Resources Bulletin*, severe drought and flood impacts in 2008 damaged the WEF system, causing a decline in security levels. From 2009 to 2015, comprehensive management continued to deepen, and WEF system security gradually improved. By the end of 2020, with the full implementation of the river and lake chief system, targeted poverty alleviation, and ecological protection, WEF system security improved rapidly.

Additionally, WEF system security in Xinjiang exhibited a spatial pattern of “high in the north, low in the south, with contiguous expansion of core areas”

(Figure 6). In 2005, the Kashgar region, Aksu region, Bayingolin Mongol Autonomous Prefecture, Hami City, and Bortala Mongol Autonomous Prefecture were in a very unsafe state. By 2014, these regions had improved to unsafe status, while Tacheng region and Changji Hui Autonomous Prefecture improved to basically safe status. In 2017, Ili Kazak Autonomous Prefecture improved to basically safe status, and all other regions escaped the very unsafe state, with the entire region entering an unsafe state spatially. By 2020, WEF system security levels had significantly improved, with Kashgar, Aksu, Bayingolin, and Altay regions upgrading to basically safe status. In 2023, security levels further improved, with unsafe, basically safe, and comparatively safe conditions coexisting across the region, and spatial differences further expanded.

2.3 Coupling Coordination Analysis

2.3.1 Temporal Changes in Coupling Coordination Degree The coupling coordination degree between ecosystem services and WEF system security in Xinjiang showed an overall upward trend (Figure 7), increasing from mild disorder to critical coordination with a relatively fast growth rate. The coupling coordination degrees for 2005, 2014, and 2023 were 0.34, 0.40, and 0.41, respectively, with average annual growth rates of 1.85%, 0.86%, and 0.34%. The growth rate gradually slowed, and the coupling coordination degree encountered a development bottleneck, requiring breakthroughs through synergistic optimization of key elements.

2.3.2 Spatial Evolution of Coupling Coordination Degree The coupling coordination degree between ecosystem services and WEF system security in 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 basic coordination area first, while the Tarim Basin in southern Xinjiang, affected by closed terrain and shortage of ecological water, showed large-scale severe disorder. By 2014, the Tarim River ecological water conveyance project in southern Xinjiang effectively improved coordination levels, significantly reducing severely disordered areas. Basic coordination areas in northern Xinjiang expanded toward the Junggar Basin, improving overall regional coordination. In 2017, basic coordination areas further extended eastward, with most areas of the Tarim Basin upgrading to critical coordination and disordered areas becoming more fragmented. In 2023, coupling coordination degree further improved across the region, with parts of western Kunlun Mountains and the Junggar Basin upgrading to critical coordination, disordered areas showing point distribution, and highly coordinated areas in the Ili River Valley shifting from point to belt distribution.

2.3.3 Spatiotemporal Evolution of Coupling Coordination by Prefecture Using the coupling coordination degree threshold of 0.5 to divide disordered and coordinated intervals, Xinjiang' s prefectures were classified into three types based on their coupling coordination levels and growth trends (Table 4): coordination-steady development type, coordination-rapid improvement type, and disorder-transformation 攻坚 type.

The coordination-steady development type includes Ili, Changji, and Tacheng, which effectively established long-term synergistic mechanisms between ecosystem services and WEF system security through technological innovation and efficient resource utilization, forming a benign development trend. The coordination-rapid improvement type includes Altay, Kashgar, Aksu, Bortala, and Kizilsu. Altay promoted ecological projects such as returning grazing land to grassland, achieving rapid growth in regional coupling coordination. Urumqi experienced rapid urban expansion in 2005, leading to excessive industrial water use and increased dependence on traditional energy sources. After optimizing industrial water-saving standards, renovating water supply networks, and increasing clean energy consumption proportions, the coordination degree fluctuated and recovered. Aksu and Kizilsu vigorously developed water-saving agriculture in irrigation districts, breaking through critical coordination thresholds.

The disorder-transformation 攻坚 type involves extensive regions constrained by dual factors of resource and industrial path dependence. Hotan suffers from extreme arid climate, uneven seasonal runoff distribution, and persistent water supply-demand contradictions, resulting in low coordination degrees. Karamay is limited by petroleum industry chain path dependence, maintaining low overall coupling coordination levels. Hami and Turpan face prominent water resource tensions due to excessively high agricultural water proportions, constraining further development of coupling coordination. Bayingolin faces conflicts between oil and gas development and ecological protection that restrict further improvement of coupling coordination.

2.4 Interaction Mechanism Analysis Using the factor detection method in geographic detector analysis, we selected land use type, watershed, elevation, precipitation, potential evapotranspiration, and soil erosion as natural elements to identify key influencing factors of ecosystem services on WEF system security spatial differentiation (Figure 9). Potential evapotranspiration and soil erosion only showed significant impacts in some years, while watershed and precipitation were long-term dominant 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 0.42, 0.45, and 0.48 in 2005, 2014, and 2023, respectively. Water resource elements have decisive effects on WEF system security in arid regions, requiring ecosystem management based on water resource carrying capacity and watershed-scale water resource regulation as key components of WEF security pattern construction.

For variables passing significance tests, we calculated mean q values (Figure 10). WEF system security factors influencing ecosystem services showed that per capita water resources ($q = 0.38$), total grain output ($q = 0.35$), water resource development and utilization rate ($q = 0.33$), and grain yield per unit area ($q = 0.31$) were key factors, followed by agricultural machinery power ($q = 0.29$). Compared with energy development, water resource utilization and agricultural production have stronger impacts on ecosystem services. After 2015, q values of various factors fluctuated sharply before stabilizing, with the explanatory power of single factors on ecosystem services generally weakening while multi-element joint effects gradually became dominant.

3. Discussion

Various components of ecosystems interact and influence each other, affecting the same or different ecosystem services. Changes in forest and grassland areas directly affect ecological source integrity and service synergy by regulating vegetation canopy density and root consolidation depth. 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. Water yield shows typical climate-driven characteristics. High precipitation and low potential evapotranspiration in the Ili River basin jointly support high water yield, consistent with long-term observation data from Chen et al. High habitat quality and soil retention capacity in the Ili River Valley synergistically improve, demonstrating vegetation' s soil consolidation ability and validating the spatial coupling pattern between biodiversity and service functions proposed by Zhang et al.

The WEF system security pattern in Xinjiang shows significant spatial heterogeneity of "high in the north, low in the south," primarily due to regional imbalances in technological innovation capacity and resource utilization efficiency. Water consumption per unit GDP, energy consumption per unit GDP, and water-saving irrigation area constitute core driving factors of system security. The northern Tianshan slope has formed a virtuous cycle of "using energy to save water and using water to promote grain" through water-saving technology promotion and coordinated wind-solar energy development, improving WEF system security. In contrast, the Tarim Basin is limited by scarce precipitation, strong evaporation, and lagging water-saving technology 普及, combined with groundwater over-exploitation and farmland abandonment, resulting in lower WEF system security levels.

The coupling coordination degree between ecosystem services and WEF systems in Xinjiang presents an evolution pattern of "northern Xinjiang optimization leading, southern Xinjiang gradient catching up." Northern Xinjiang has enhanced food system security through water-saving irrigation technology 普及 and wind-solar energy substitution. Water-saving technology applications not only enhance agricultural production stability but also reduce dependence on limited water resources. Studies in Iran' s semi-arid regions have also revealed that high-input agricultural systems produce higher yields but also incur higher environmental costs and negative externalities, emphasizing the need for water resource management to balance productivity and environmental protection. Southern Xinjiang faces more prominent water-energy competition contradictions due to resource-intensive industrial structures, groundwater over-exploitation, and severe farmland fragmentation, showing concentrated distribution of mild disorder. In recent years, promoting water-saving technologies and improving land use efficiency in southern Xinjiang has led to localized improvements, with marginal oases primarily showing basic coordination and sporadic high coordination areas, though the overall coupling coordination level still lags significantly behind northern Xinjiang.

The WEF security indicator system in this study still has certain limitations. Future research could improve scientific validity by constructing more comprehensive indicator systems, enhance precision by reducing study units, and provide more targeted policy recommendations.

4. Conclusions and Recommendations

4.1 Conclusions Based on the InVEST model, accelerated genetic algorithm projection pursuit model, and coupling coordination degree model, this study quantified ecosystem services and WEF system security, analyzed their coupling coordination relationship, and identified interaction mechanisms through geographic detector analysis. The conclusions are as follows:

(1) From 2005 to 2023, ecosystem services in Xinjiang remained generally stable, with obvious spatial differentiation characteristics spreading from oasis areas outward. Water yield first increased, then decreased, and increased again; habitat quality remained basically stable; carbon storage increased slowly; and soil retention showed a fluctuating downward trend.

(2) WEF system security in the study area showed an overall upward trend, gradually improving from an unsafe state to a basically safe state, with a spatial pattern of "high in the north, low in the south, and contiguous expansion of core areas."

(3) The coupling coordination degree between ecosystem services and WEF system security displayed a "high in the north, low in the south" distribution pattern, progressing from mild disorder to critical coordination with a gradually slowing annual growth rate. Water scarcity and spatial misallocation have intensified structural contradictions in synergistic system development, urgently requiring breakthroughs through improved resource utilization efficiency.

(4) 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' s vast territory encompasses diverse ecosystems, with intertwined complexities of urban, industrial, energy, and ecological issues requiring effective integration across conceptual, technological, policy, and management levels to flexibly adapt to arid region ecosystem thresholds and scientifically realize resource environmental values.

(1) **Strengthen ecological barrier functions and improve resource utilization efficiency.** Enhance 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, advance salinization control and sand fixation projects to enhance water conservation and soil retention capacity, curbing ecosystem service function degradation.

(2) **Promote industrial optimization and transformation, and strengthen regional collaborative governance.** Based on resource endowments and location advantages, deepen opening-up cooperation and technological innovation to promote upgrading of traditional industries and integration with emerging business forms.

(3) **Improve ecological environment zoning and strengthen dynamic regulation.** Emphasize watershed-scale water resource management, enhance regional cooperation, coordinate water-energy-food system interactions, optimize spatial suitability of resource utilization, and implement systematic management of mountains, rivers, forests, farmlands, lakes, grasslands, and deserts. Scientifically delineate ecological environment zones, establish risk warning threshold response mechanisms, and achieve hierarchical response and dynamic regulation to improve spatial governance precision and adaptability.

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