Ecosystem Services Supply-Demand Matching Based on the Water-Energy-Food Nexus: A Case Study of the Urban Agglomeration on the Northern Slope of the Tianshan Mountains (Postprint)

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Abstract

Water, energy, and food are important components of ecosystem services, holding significant importance for supply-demand balance and regional high-quality development. Employing methods including the InVEST model, Supply-Demand Matching Degree (SDMD), and Pearson correlation analysis, we quantified the spatiotemporal characteristics of four ecosystem services—water yield, carbon sequestration, soil conservation, and food production—in the urban agglomeration on the northern slope of the Tianshan Mountains from 2000 to 2020, and explored the spatial heterogeneity of supply-demand matching at different scales. The results show that: (1) The supply of food production service in the study area displayed an overall upward trend, whereas the supply of water yield, carbon sequestration, and soil conservation services exhibited a downward trend. The demand for water yield, carbon sequestration, soil conservation, and food production services all demonstrated an upward trend. (2) The supply of water yield and food production services in the study area showed a west-high, east-low pattern, while demand overlapped with densely populated areas in a punctate distribution. Carbon sequestration service supply was high in the southwest and central regions and low in the northeast, whereas soil conservation service supply and demand exhibited punctate high values distributed in the Tianshan Mountains, with roughly identical spatial distributions of supply and demand. (3) The SDMD of soil conservation and food production services increased, while the SDMD of water yield and carbon sequestration services decreased. SDMD exhibited spatial heterogeneity at different scales, most pronounced at the grid scale. (4) The spatial differentiation of different ecosystem services was significant;

zonal control-categorical optimization-graded management constitutes an effective comprehensive control strategy that can provide scientific support for the high-quality economic and social development, ecological environmental protection, and restoration of the urban agglomeration on the northern slope of the Tianshan Mountains.

Full Text

Preamble

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Matching between Supply and Demand of Ecosystem Services Based on the "Water-Energy-Food" Nexus: A Case Study of the Urban Agglomeration on the Northern Slope of the Tianshan Mountains

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Abstract: Water, energy, and food are critical components of ecosystem services that significantly influence supply-demand balance and high-quality regional development. Using the InVEST model, supply-demand matching degree (SDMD), Pearson correlation analysis, and related methods, this study quantifies the spatiotemporal characteristics of four ecosystem services—water yield, carbon sequestration, soil conservation, and food production—in the urban agglomeration on the northern slope of the Tianshan Mountains from 2000 to 2020, and explores the spatial heterogeneity of supply-demand matching across different scales. The results indicate that: (1) The overall supply of food production services in the study area showed an upward trend, while the supply of water yield, carbon sequestration, and soil conservation services declined. Demand for all four services increased. (2) The supply of water yield and food production services was higher in the west and lower in the east, while demand exhibited point-like distributions overlapping with densely populated areas. Carbon sequestration service supply was high in the southwest and central regions but low in the northeast. Soil conservation service supply and demand both showed point-like high-value distributions in the Tianshan Mountains, with roughly aligned spatial patterns. (3) The SDMD for soil conservation and food production services increased, whereas the SDMD for water yield and carbon sequestration services decreased. SDMD exhibited spatial heterogeneity across different scales, with the most significant variations observed at the grid scale. (4) The spatial differentiation of ecosystem services was evident, and differentiated control strategies with hierarchical governance are needed. These findings provide scientific support for high-quality economic and social development, ecological

protection, and restoration in the urban agglomeration on the northern slope of the Tianshan Mountains.

Keywords: "water-energy-food" nexus; ecosystem services; supply-demand matching; InVEST model

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1. Introduction

Rapid economic development in China has triggered a series of social, economic, cultural, and environmental issues. Urban expansion continuously encroaches upon and weakens ecological spaces, while surface hardening and increasing energy and food demands alter the ecological environment of urban agglomerations, thereby affecting the supply and demand services that ecosystems provide directly or indirectly. Water, energy, and food are fundamental to human survival and development, influencing urban development and the rise and fall of civilizations. These three elements are not only closely interrelated but also complexly associated with ecosystem services. Addressing the "water-energy-food" relationship not only provides support and guarantees for ecological patterns and security but also enables the sustainable utilization of critical resources to the maximum extent within limited regions.

Since the 1980s, scholars worldwide have begun focusing on ecosystem services and the relationships among their components, gradually shifting from conceptual interpretation and framework definition to the quantification of supply and demand services. Currently, quantitative models, spatial overlay analysis, and process-based models are commonly used to assess the spatial characteristics and matching relationships of ecosystem service supply and demand for vegetation, soil, and water systems at different scales based on statistical data and remote sensing imagery. Ecosystem services play a crucial supporting role in urban development, affecting regional water, energy, and food security and sustainability. The "water-energy-food" nexus has been identified as one of the major global security issues.

Previous studies on the relationship between the "water-energy-food" nexus and ecosystem services have primarily employed system dynamics models and coupling coordination degree methods, with research areas mainly concentrated in central and eastern coastal regions of China. For instance, Zhang et al. studied the Yangtze River Delta, An et al. focused on Northeast China, and Tang examined the Jinghe River Basin. These rich findings provide a solid foundation for future research but still have limitations. Water, energy, and food originate from ecosystems, interact with each other, and in turn affect ecosystems. Current research on the relationship between the "water-energy-food" nexus and ecosystem services remains relatively independent and lacks systematic integration. Constrained by data availability or technical methods, previous studies have emphasized supply-side analysis, with less attention paid to supply-demand matching and spatial patterns, particularly regarding zoning control. Moreover, research has concentrated on eastern coastal regions and metropolitan areas, with insufficient attention to resource-poor western arid and semi-arid regions.

The urban agglomeration on the northern slope of the Tianshan Mountains is located in the hinterland of the Eurasian continent, serving as an economic, cultural, and ecological corridor in northwest China and a launch area for the Belt and Road Initiative. In recent years, rapid urbanization has intensified contradictions between economic development and ecological protection. Issues such as water resource scarcity, unbalanced development, environmental pollution, and ecological degradation have become increasingly severe, exacerbating the imbalance in the "water-energy-food" nexus and ecosystem services in the region. Therefore, integrating the nexus relationship into ecosystem service supply-demand matching research and exploring the evolution of "water-energy-food" relationships within multidimensional ecosystem services in the study area is of great significance.

The specific objectives of this study are: (1) to briefly analyze the internal relationships and correlations within the "water-energy-food" nexus; (2) to quantify the supply and demand of ecosystem services using the InVEST model and population spatial analysis methods; (3) to evaluate the spatial clustering and correlation relationships of ecosystem service supply and demand related to the "water-energy-food" nexus using supply-demand matching degree and bivariate adaptive methods; and (4) to formulate corresponding management models based on different matching scenarios. This research helps understand resource imbalances and rational allocation issues in the urban agglomeration on the northern slope of the Tianshan Mountains, providing scientific support for regional ecological protection and high-quality economic and social development.

1.1 Study Area

The urban agglomeration on the northern slope of the Tianshan Mountains (42°25 -46°21 N, 79°88 -91°56 E) is located on the northern foothills of the Tianshan Mountains in northwestern China' s border region. It encompasses Urumqi City, Tacheng Prefecture, Changji Hui Autonomous Prefecture, Shihezi City, Yili Kazakh Autonomous Prefecture (directly-administered counties and cities), Bortala Mongol Autonomous Prefecture, Huyanghe City, Kokdala City, Karamay City, Shuanghe City, Wujiaqu City, and the 7th Division of the Xinjiang

Production and Construction Corps—totaling 11 cities (Fig. 1). The territorial area is 2.045$\times10^{5}$ km^2 with a population of 1.0977$\times10^{7}$. The region has a typical temperate continental climate with low annual precipitation, generally less than 200 mm except in the Yili River Valley. The Tianshan Mountains form an inverted “S” shape across the region from east to west, with terrain sloping from high in the southwest to low in the northeast, creating substantial elevation differences. The area is rich in mineral resources, has a unique geographical location, and relatively good infrastructure, making it an important development pole for China’ s Western Development Strategy and a key launch area and hub for the Belt and Road Initiative. However, the region’ s dry climate and fragile ecology mean that high-intensity development and construction may exacerbate ecological degradation risks.

1.2 Data Sources and Preprocessing

This study involves multiple datasets, with specific sources detailed in Table 1. ArcGIS 10.6 software was used to perform uniform data preprocessing, including projection transformation, clipping, and resampling to a 1 km$\times$1 km grid under the same coordinate system (1984_{{{UTM}}*{{Zone}}}*{45N}) before conducting spatial statistics and analysis.

1.3 “Water-Energy-Food” Nexus Analysis Framework

Water, energy, and food are inseparable from urban agglomeration social-ecological systems, comprising both supply and demand components. Important correlations exist between the supply and demand of each element, making the “water-energy-food” nexus relationship highly sensitive, where a single change can affect the entire system. Due to mutual constraints, water, energy, and food typically do not grow without limit individually but instead form a dynamic equilibrium state. The nexus exhibits four key causal relationships: (1) Water scarcity leads to reduced agricultural production, directly decreasing agricultural water use and thereby alleviating water shortages; (2) Energy extraction consumes substantial water resources, and water scarcity weakens energy activities, reducing industrial water consumption and alleviating water shortages; (3) Energy shortages reduce agricultural production capacity, decreasing agricultural water use and thereby alleviating energy shortages to some extent; and (4) The interrelationships are illustrated in Figure 2.

1.4.1 Quantification Methods for Ecosystem Service Supply and Demand

Water Yield Service Supply and Demand Quantification

Water yield services primarily include vegetation interception of precipitation, water retention by litter layers, and soil water storage. Parameters such as maximum root depth, plant evapotranspiration coefficient, and plant available water content were derived from empirical values in relevant studies. The InVEST model calculates water yield for each grid cell based on the Budyko curve and annual precipitation. The specific formula is as follows:

$$Y_{t,i} = P_{t,i} - E_{t,i}$$

where $Y_{t,i}$ is the water yield for grid cell i in year t (mm), $E_{t,i}$ is the actual evapotranspiration for grid cell i in year t (mm), and $P_{t,i}$ is the precipitation for grid cell i in year t (mm).

Water demand comprises the total water required for agriculture, industry, and domestic activities. Population spatial distribution data were used to allocate water demand to individual grid cells. The specific formula is:

$$D_{t,g} = \frac{D_t \times P_{t,g}}{P_t}$$

where $D_{t,g}$ is the water demand for grid cell g in year t (mm), D_t is the total water demand in year t (mm), $P_{t,g}$ is the population count for grid cell g in year t (people), and P_t is the total permanent population in year t (people).

Carbon Sequestration Service Supply and Demand Quantification

Carbon sequestration service supply includes both plant carbon sequestration and soil carbon sequestration. Parameters for aboveground biomass, belowground biomass, soil carbon pools, and dead organic matter carbon pools were derived from empirical values in relevant studies. The specific formula is:

$$C_{t,g} = C_{t,g}^{\text{above}} + C_{t,g}^{\text{soil}} + C_{t,g}^{\text{below}} + C_{t,g}^{\text{dead}}$$

where $C_{t,g}$ is the carbon sequestration amount for grid cell g in year t ($\text{t} \cdot \text{hm}^{-2}$), and the terms represent carbon sequestration in aboveground biomass, soil, belowground biomass, and dead organic matter, respectively.

Carbon sequestration service demand was calculated by multiplying energy consumption by corresponding carbon emission factors, then computing per capita carbon emissions, and finally multiplying by population spatial distribution to obtain carbon emissions for different grid cells. The specific formula is:

$$C_{t,g}^{\text{demand}} = \frac{C_t \times P_{t,g}}{P_t}$$

where $C_{t,g}^{\text{demand}}$ is the carbon emission for grid cell g in year t ($\text{t} \cdot \text{hm}^{-2}$), C_t is the total carbon emission in year t (t), and P_t is the total energy consumption in year t.

Soil Conservation Service Supply and Demand Quantification

Soil conservation service supply derives from land use’ s erosion resistance and sediment water retention capacity. The specific formula is:

$$SC_{t,g} = R_{t,g} \times K_{t,g} \times LS_{t,g} \times (1 - C_{t,g} \times P_{t,g})$$

where $SC_{t,g}$ is the soil conservation amount for grid cell g in year t ($\mathrm{t} \cdot \mathrm{hm}^{-2}$), $R_{t,g}$ is the rainfall erosivity factor, $K_{t,g}$ is the soil erodibility factor, $LS_{t,g}$ is the slope length factor, $C_{t,g}$ is the vegetation cover factor, and $P_{t,g}$ is the soil conservation practice factor.

Soil conservation service demand is based on the principle of land degradation neutrality, with actual soil erosion amount used as the baseline. The specific formula is:

$$SC^{\mathrm{demand}}_{t,g} = R_{t,g} \times K_{t,g} \times LS_{t,g}$$

Food Production Service Supply and Demand Quantification

A significant linear relationship exists between the Normalized Difference Vegetation Index (NDVI) and grain yield per unit area. NDVI was used to estimate grain yield at the grid cell scale, which was then aggregated to different grid cells. The specific formula is:

$$G_{t,g} = G^{\mathrm{sum}}_{t} \times \frac{\mathrm{NDVI}_{t,g} \times A_{t,g}}{\sum(\mathrm{NDVI}_{t,g} \times A_{t,g})}$$

where $G_{t,g}$ is the food production amount for grid cell g in year t ($\mathrm{t} \cdot \mathrm{hm}^{-2}$), G^{sum}_{t} is the total grain production for a city in year t (t), and $A_{t,g}$ is the cultivated land area for grid cell g in year t (hm^2).

Food production service demand was obtained by multiplying per capita food consumption by population spatial distribution. The specific formula is:

$$D^{\mathrm{food}}_{t,g} = C^{\mathrm{food}}_{t} \times P_{t,g}$$

where $D^{\mathrm{food}}_{t,g}$ is the food demand for grid cell g in year t ($\mathrm{t} \cdot \mathrm{hm}^{-2}$) and C^{food}_{t} is the per capita food consumption in year t ($\mathrm{t} \cdot \mathrm{person}^{-1}$).

1.4.2 Analysis Methods for Ecosystem Service Supply-Demand Matching

Supply-Demand Matching Analysis

The supply-demand matching degree (SDMD) model connects actual ecosystem service supply with human demand, evaluating the quantitative matching characteristics. The formula is:

$$\mathrm{SDMD}_{t,g} = \frac{S_{t,g} - S_{t,g}^{\max} + D_{t,g} - D_{t,g}^{\max}}{2}$$

where $\mathrm{SDMD}_{t,g}$ is the supply-demand matching degree for grid cell g in year t, $S_{t,g}$ and $D_{t,g}$ are the supply and demand of ecosystem services, and $S_{t,g}^{\max}$ and $D_{t,g}^{\max}$ are the maximum supply and demand values. Positive values indicate supply surplus, zero indicates balance, and negative values indicate supply deficit.

Spatial Agglomeration Analysis

A quadrant classification method was used to analyze the spatial agglomeration of ecosystem service supply and demand. The x-axis represents standardized ecosystem service supply, and the y-axis represents standardized demand. The formulas for standardization are:

$$Z_{t,g}^{S} = \frac{S_{t,g} - \bar{S}_t}{\sigma_t^S}, \quad Z_{t,g}^{D} = \frac{D_{t,g} - \bar{D}_t}{\sigma_t^D}$$

where $Z_{t,g}^{S}$ and $Z_{t,g}^{D}$ are standardized values, $\bar{S}_t$ and $\bar{D}_t$ are means, and σ_t^S and σ_t^D are standard deviations. After obtaining standardized values at the pixel scale, Geoda spatial analysis tools were used to generate spatial distributions across four quadrants.

Correlation Analysis

Pearson correlation analysis was used to evaluate relationships between total supply of each ecosystem service and evaluation values of subsystems within the “water-energy-food” nexus. A correlation coefficient significantly greater than 0 indicates a positive relationship, while a coefficient significantly less than 0 indicates a negative relationship.

Comprehensive Management Method

First, based on the supply-demand status of each subsystem, dominant ecosystem services were identified through quantitative comparison of standardized results, and units were classified into water resource zones, energy zones, food zones, and soil conservation zones. Second, standardized ecosystem services were overlaid to determine spatial clustering relationships. High supply-high demand areas were designated as protection zones (high-high clustering) requiring regular maintenance; high supply-low demand areas as conservation zones (high-low clustering) suitable for moderate protection; low supply-high demand areas as improvement zones (low-high clustering) requiring priority ecological enhancement; and low supply-low demand areas as reconstruction zones (low-low clustering) needing fundamental ecological restoration. Finally, from an overall perspective, the standardized SDMD was divided into priority control zones, key control zones, and general control zones using the natural breaks method, establishing management priorities based on urgency.

2.1 Spatiotemporal Characteristics of Ecosystem Service Supply-Demand Matching

2.1.1 Temporal Characteristics

From 2000 to 2020, the supply-demand contradiction for water yield services in the urban agglomeration on the northern slope of the Tianshan Mountains continuously intensified. Water yield supply peaked around 2015 then declined, while demand maintained an overall upward trend, reaching its maximum gap in 2020 (Table 2). The total supply of carbon sequestration services far exceeded demand, but supply capacity showed a declining trend while demand continuously increased due to extensive fossil fuel use, leading to increasingly acute local supply-demand contradictions—closely related to the region' s rapid socioeconomic development and ongoing industrialization. Soil conservation service supply and demand both showed initial increases followed by decreases, with the largest gap occurring in 2015 that gradually narrowed thereafter. Food production service supply far exceeded demand, but supply peaked in 2015 due to industrialization, urbanization, and implementation of the Grain for Green policy, while demand only changed steadily with dietary structure and population.

2.1.2 Spatial Characteristics

The supply of ecosystem services in the urban agglomeration on the northern slope of the Tianshan Mountains showed complex spatial patterns from 2000 to 2020 (Fig. 3). High water yield supply areas were distributed in the western and southwestern regions, primarily influenced by precipitation factors. These high-supply areas gradually expanded eastward over time, related to topographic characteristics and warming-wetting trends. High carbon sequestration and soil conservation supply areas were concentrated in the central-western and southwestern mountainous regions, mainly in land use types such as cultivated land, forest, grassland, and water bodies, with low supply in densely populated and desert areas. High food production supply areas were concentrated in southwestern and central oases, primarily in river valleys or alluvial plains at mountain fronts with abundant cultivated land resources.

Ecosystem service demand showed high consistency with population spatial distribution (Fig. 4). High water yield demand areas were concentrated in densely populated and industrial zones such as Changji Hui Autonomous Prefecture, Urumqi City, and Karamay City, showing strip-like distributions. High carbon sequestration demand areas were mainly concentrated in Karamay City, northern Changji Hui Autonomous Prefecture, Urumqi City, and the Kashgar River Valley, where rapid industrial development generated large carbon emissions. High soil conservation demand areas were concentrated in mountainous regions where seasonal floods created significant erosion. High food production demand areas were concentrated in Urumqi City and the Yili River Valley, showing point-like or band-like distributions.

The spatial heterogeneity of ecosystem service supply-demand matching was evident (Fig. 5). Low water yield matching areas showed point-like distributions, particularly in industrially and densely populated urban areas where low precipitation and high demand resulted in extremely poor spatial matching and supply shortages. Carbon sequestration matching was high in central and western oases and low in northern and northeastern deserts, though overall supply far exceeded demand given the region’ s vast land area and sparse population, maintaining good matching despite recent rapid emission increases. Soil conservation matching was generally balanced, but supply fell short of demand in northern and northeastern deserts and at the front edge of the Tianshan Mountains. Food service matching was greater than 0 in most areas, indicating overall supply surplus, and spatial matching gradually improved over time.

2.2 Correlation Analysis between Ecosystem Service Supply and Demand

Ecosystem service supply-demand matching in the urban agglomeration showed significant spatial heterogeneity (Fig. 6). Water yield matching exhibited low-low and high-low clustering patterns that were not uniform, with low-low clusters mainly on the northern slope of the Tianshan Mountains and high-low clusters in northeastern deserts and Urumqi City. Carbon sequestration and food production matching showed similar spatial clustering characteristics, with high-high and low-high clusters concentrated in densely populated urban areas and their surroundings. Over time, low-high clustering became more pronounced and expanded in distribution. Soil conservation matching showed high-high and low-low clusters, with high-high and low-high clusters distributed near the Tianshan Mountains where soil conservation and accumulation effects were significant.

Pearson correlation analysis revealed significant differences in ecosystem service supply-demand relationships across scales (Fig. 7). As spatial scale decreased, correlations gradually strengthened, with grid-scale relationships reaching statistical significance ($P < 0.05$). Ecosystem service supply-demand relationships showed correlations both overall and among different supply/demand categories, particularly for carbon sequestration supply. From the SDMD perspective, ecosystem service supply-demand matching gradually strengthened, with correlations shifting toward positive values. Significant scale effects existed, with smaller scales showing more pronounced spatial heterogeneity in matching. To balance regional management and supply-demand relationships, the county-level administrative unit was selected as the standard unit for integrated management.

2.3 Comprehensive Management Strategies from the “Water-Energy-Food” Perspective

The spatial differentiation of ecosystem services in the urban agglomeration was evident (Fig. 8). By zone type, energy zones accounted for 48.78% of units, while water resource zones and food zones were fewer at 4.88% each. Soil conservation zones accounted for 14.63% and were distributed in the Tianshan Mountains. By category, protection zones were mainly in the west (31.71%), improvement and conservation zones each accounted for 17.07% and were mainly in the central-west, and reconstruction zones accounted for 19.51% and were mainly in the east. By management level, the overall situation was relatively good with few priority control zones (9.75%), mainly in Urumqi City and surrounding units. Key control zones were most numerous (53.66%), widely distributed in eastern and central areas. General control zones accounted for 36.59% and were mainly in the west.

Overlaying the "zoning control + hierarchical governance"results yielded 16 management zone combinations. Water resource zones included general protection and key improvement subzones. Energy zones included key protection, general conservation, key conservation, key reconstruction, and key improvement subzones. Food zones included general conservation, priority conservation, and priority reconstruction subzones. Soil conservation zones included general protection, key protection, and general improvement subzones. Conservation and improvement zones were most numerous and concentrated in densely populated areas.

3. Discussion

3.1 Supply-Demand Matching and Dynamic Changes

Natural resource endowments and changing human demands determine ecosystem service supply-demand matching and dynamics. Our results show that from 2000 to 2020, food production service supply in the urban agglomeration increased from 0.10 $t \cdot hm^{-2}$ to 0.12 $t \cdot hm^{-2}$, maintaining an overall upward trend, while water yield, carbon sequestration, and soil conservation service supply declined. Except for a demand decrease in 2015, all four services maintained an upward trend of about 3%–30%. Consequently, the SDMD for water yield and carbon sequestration decreased, while the SDMD for soil conservation and food production increased. The main reasons are the continuous improvement in industrialization and urbanization levels in the region, leading to expanding resource demand and increased supply pressure. Meanwhile, production areas for water and energy services remain relatively fixed, exacerbating spatial mismatches between supply and demand.

In 2015, the central government intensified the implementation of the Grain for Green policy, expanding and improving forest and grassland areas, which improved ecosystem service supply to some extent. Analysis of spatial agglomeration patterns shows that subsystem services mostly exhibited low-low and high-low clustering, indicating large spatial disparities and extensive low-quality distribution. In the future, different regions and subsystems can appropriately allocate resources to each other based on complementary advantages for rational and efficient configuration to promote high-quality development.

3.2 Influence of Spatial Scale on Supply-Demand Matching

Ecosystem service supply-demand relationships show different correlations and significant spatial heterogeneity across scales. This study demonstrates that differences in SDMD are significant at the grid scale. As spatial scale increases, the spatial pattern of matching shifts from high-high clustering to low-low and low-high clustering. At municipal and county scales, as spatial scale decreases, spatial heterogeneity in SDMD becomes more pronounced, reflecting more obvious spatial mismatches at medium and small scales. To deeply explore scale effects, correlation analysis was conducted, revealing complex trade-offs and synergies among ecosystem services across scales. Specifically, at the county scale, water yield services showed trade-off relationships, while other services showed synergistic relationships. Additionally, ecosystem service supply, demand, and matching at the county scale all met statistical significance requirements ($P < 0.05$), making the county scale suitable as the basic unit for ecological management.

3.3 Management Implications for the Urban Agglomeration

Industrialization and urbanization have intensified spatial mismatches in ecosystem service supply and demand. Future management should follow the "zoning control + hierarchical governance" framework. (1) **Scientific zoning for rational allocation**: Consider spatial trade-offs and synergies among different ecosystem services to sustainably maximize service functions. Energy zones, soil conservation zones, and food zones account for 48.78%, 14.63%, and 31.71% respectively, requiring differentiated development strategies. Water resource zones should improve cross-regional allocation mechanisms to address water security. Energy zones should leverage resource advantages while emphasizing water conservation, energy saving, and emission reduction to achieve coordinated resource development and environmental protection. Food zones should actively adjust planting and management models, practice the "Big Food" concept, and achieve diversified food supply alongside staple grains. Soil conservation zones should strictly adhere to land use controls to prevent ecological degradation and promote ecological security.

(2) **Optimized classification with differentiated policies**: Classify areas by urgency based on supply-demand matching differences for integrated management. Key control zones and general control zones involve numerous counties (36.59% and 53.66% respectively), while priority control zones are smaller (9.75%), indicating relatively minor ecological problems. Improvement and conservation zones account for 31.71% and 17.07% respectively, concentrated in urban development areas that should adopt conservation-oriented development models to reduce negative environmental impacts. Protection zones are mainly in remote areas and should explore ecological industrialization mechanisms to promote coordinated ecological and economic growth. Ecological reconstruction zones are mostly ecologically fragile areas that should delimit ecological protection redlines,

respect natural processes, and implement moderate restoration.

This study has several limitations. First, data availability constraints limited the analysis to four key ecosystem services closely related to the "water-energy-food" nexus; future research could incorporate additional services. Second, this study did not deeply consider social development and policy orientation issues, which could be integrated into matching models in future work. Finally, the study treated the urban agglomeration as a relatively closed system, with limited consideration of potential external ecological influences.

4. Conclusions

(1) **Temporal trends**: Food production service supply in the urban agglomeration on the northern slope of the Tianshan Mountains showed an overall upward trend from 2000 to 2020, while water yield, carbon sequestration, and soil conservation service supply declined. Socioeconomic development drove continuously increasing demand for all four services. The SDMD for water yield and carbon sequestration decreased, while the SDMD for soil conservation and food production increased.

(2) **Spatial patterns**: Water yield and food production supplies were higher in the west and lower in the east, with demand and matching patterns showing point-like distributions in densely populated areas. Carbon sequestration supply and matching were high in the southwest and central regions but low in the northeast, with demand showing point-like distributions. Soil conservation service supply, demand, and matching all showed point-like high-value distributions near the Tianshan Mountains.

(3) **Scale effects**: Ecosystem service supply-demand matching exhibited spatial heterogeneity across scales, with the most significant correlations at the grid scale. Different ecosystem services predominantly showed high-low clustering patterns in their spatial agglomeration.

(4) **Management implications**: The "zoning control + hierarchical governance" approach should be implemented, with county-level administrative units as the basic management units. Differentiated development strategies and governance policies should be formulated based on the supply-demand status and matching patterns of different ecosystem services.

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