

Postprint: Spatial Matching Characteristics of Ecosystem Services Supply and Demand in the Shule River Basin

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Abstract

Ecosystem services are intrinsically linked to human sustainable development. Investigating the supply-demand characteristics of regional ecosystem services and understanding their spatial matching patterns constitute crucial prerequisites for effective ecological resource allocation and regional ecological security enhancement. Based on multi-source data and utilizing the InVEST model, ArcGIS, and GeoDA software, this study examines the supply-demand dynamics and spatial congruence of water yield, carbon sequestration, and food provisioning services in the Shule River Basin. The findings reveal that: (1) Except for water yield service, the supply of all other ecosystem services exceeds demand across the Shule River Basin, though variations exist among different regions and service types. (2) The comprehensive supply-demand ratio for the basin is 0.063, with individual ecosystem services exhibiting the following descending order: carbon sequestration service (0.1854), food service (0.0078), and water yield service (-0.0043). (3) Both water yield and carbon sequestration services predominantly exhibit low-high and high-low spatial mismatch patterns, whereas food service primarily demonstrates low-low spatial matching, with water yield service manifesting the most severe spatial mismatch phenomenon.

Full Text

Spatial Matching Characteristics of Supply and Demand of Ecosystem Services in the Shule River Basin

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Abstract: Ecosystem services are closely linked to sustainable human development. Analyzing the supply and demand characteristics of regional ecosystem services and understanding their spatial matching status are essential prerequisites for achieving efficient allocation of ecological resources and promoting regional ecological security. Based on multisource data and supported by the InVEST model, ArcGIS, and GeoDA software, this study examines the supply and demand characteristics of water production, carbon sequestration, and food services in the Shule River Basin, as well as their spatial matching patterns. The results indicate that: (1) Except for water production services, the supply of other ecosystem services in the Shule River Basin exceeds demand, though variations exist across different regions and service types. (2) The comprehensive supply-demand ratio for the Shule River Basin is 0.063, with individual ecosystem service supply-demand ratios decreasing in the following order: carbon sequestration services (0.1854) > food services (0.0078) > water production services (−0.0043). (3) The spatial matching patterns for water production and carbon sequestration services are primarily characterized by low-high and high-low type spatial mismatches, while food services are mainly dominated by low-low type spatial matching, with water production services exhibiting the most severe spatial mismatch.

Keywords: ecosystem services; supply-demand relationship; spatial matching; Shule River Basin

Introduction

Rapid economic development has intensified pressure on ecological environments, leading to successive problems such as land degradation, drought, desertification, and biodiversity loss, which threaten human living environments. Ecosystem service functions constitute the material foundation for sustaining human survival and supporting the Earth's life system, as all resources required for human survival and development ultimately originate from natural ecosystems. The Chinese government has successively issued policy guidelines including the *National Master Plan for Important Ecosystem Protection and Restoration Major Projects (2021-2035)*, the *Guidelines for Mountains-Waters-Forests-Farmlands-Lakes-Grasslands Ecological Protection and Restoration Projects (Trial)*, and the *Opinions on Deepening the Reform of the Ecological Protection Compensation System* to safeguard national ecological construction, improve ecosystem functions, accelerate ecological civilization system reform, and build a beautiful China. Therefore, it is particularly important to thoroughly investigate the supply-demand relationships of ecosystem services

and reveal their spatial distribution patterns.

Ecosystem service supply and demand constitute the dynamic process of ecosystem services flowing from natural ecosystems to human social systems. Recent research on ecosystem service supply and demand has primarily focused on quantification, spatiotemporal evolution of supply-demand relationships at different scales, and ecosystem service flows. Most studies have employed methods such as ecosystem service value equivalents, land use estimation, and expert evaluation matrices. Research scales have mainly concentrated on watershed, municipal, and global scales, with relatively fewer studies at smaller scales. Foreign scholars have conducted numerous studies on ecosystem service supply and demand. Costanza and Wolff first assessed global ecosystem service values. Other researchers have mapped human demand for insect pollination, wild medicinal plants, and outdoor recreation at global scales, quantified grain supply and demand, mapped European ecosystem service supply-demand relationships, and investigated relationships among multiple ecosystem service supply, flow, and demand clusters in the European Alps.

Research on ecosystem service supply and demand in China started relatively late, primarily focusing on theoretical studies. Some scholars have examined spatiotemporal changes in ecosystem service supply and demand. For instance, Liu Licheng et al. selected multiple ecosystem service indicators to study supply-demand matching in loess hilly regions; Li Cheng et al. used the ecosystem service supply-demand evaluation matrix method proposed by Burkhard to analyze supply-demand patterns; Zhao Xueyan employed four ecosystem service indicators to reflect spatiotemporal changes in ecosystem service supply and demand; and Hu Qiyu et al. coupled ecosystem service supply and demand with landscape ecological security patterns to explore ecological spatial structure in urban agglomeration areas, thereby optimizing agricultural ecological network spatial layout.

The Shule River Basin is one of the three major inland river basins in the Hexi Corridor region and is located in the northern sand prevention belt within China's "Two Screens and Three Belts" ecological security framework, serving as an important ecological barrier. The basin experiences scarce and extremely unevenly distributed precipitation, with a fragile ecological environment representing the most severely arid region in Gansu Province. This severely constrains ecological sustainable development in the area. Studying ecosystem service supply and demand holds significant reference value for achieving ecological security. Currently, no research exists on ecosystem service supply and demand in the Shule River Basin, making it necessary to clarify the regional ecosystem service supply-demand pattern to provide a basis for scientific and effective resource allocation. In summary, this paper selects the Shule River Basin as the study area, chooses three ecosystem services—water production, carbon sequestration, and food—and analyzes the spatial supply-demand characteristics and matching status of each ecosystem service to provide theoretical support for ecosystem optimization in the Shule River Basin.

[Figure 1: see original paper]

1 Study Area Overview

The Shule River Basin (93°22' -98°59' E, 38°10' -42°47' N) is located at the western end of the Hexi Corridor in Gansu Province, covering an area of approximately 1.12×10^5 km². The terrain slopes from high in the south to low in the north, with elevations ranging from 802 to 5,504 m. The basin receives little precipitation and experiences high evaporation, forming an inland river system replenished by alpine snow and ice meltwater and mountain precipitation. The upstream mountainous area features steep slopes and rapid water flow, with typical continental perennial glaciers and extensive permafrost development, serving as the entire basin's runoff generation and water source conservation zone. The middle and downstream areas have flat terrain with coexisting oases and deserts, and extremely fragile natural environments. The Shule River Basin encompasses parts of Subei Mongolian Autonomous County, Guazhou County, Yumen City, Dunhuang City, and Aksai Kazakh Autonomous County (hereinafter referred to as Aksai County). Subei Mongolian Autonomous County includes northern Subei (hereinafter referred to as Subei (North)) and southern Subei (hereinafter referred to as Subei (South)).

2.1 Data Sources

The data sources for this study include: (1) Land use data for 2020 from the Globeland30 global geographic information public product; (2) Normalized Difference Vegetation Index (NDVI) data for 2020 from the National Tibetan Plateau Scientific Data Center (<http://data.tpdc.ac.cn/zh-hans/>); (3) Population raster data for 2020 from WorldPop (<https://www.worldpop.org>); (4) Gross Domestic Product (GDP) density raster data for 2020 from the Chinese Academy of Sciences Resource and Environmental Science Data Center (<https://www.resdc.cn>); (5) Energy consumption and water resource consumption data from statistical yearbooks of Gansu Province and various counties in the study area; (6) Population data, food production data, and per capita water consumption for each county in the study area from national economic and social development statistical bulletins; (7) Per capita food demand and average irrigation water consumption for cultivated land from the Gansu Province Water Resources Bulletin.

2.2.1 Water Production Service

Water production service is a crucial ecosystem service that intercepts, retains, and stores precipitation and freshwater, effectively maintaining soil moisture and regulating river flow. This study employs the InVEST Water Yield module to calculate water production service supply in the Shule River Basin. The water production service demand is calculated based on population raster density, per capita water consumption, and GDP density data.

The water yield is calculated as follows:

$$WY(x) = \left(1 - \frac{AET(x)}{P(x)}\right) \times P(x)$$

where $WY(x)$ is the annual water yield for grid cell x (mm), $AET(x)$ is the annual actual evapotranspiration for grid cell x (mm), and $P(x)$ is the annual precipitation for grid cell x (mm).

The ratio of actual to potential evapotranspiration is calculated as:

$$\frac{AET(x)}{P(x)} = \frac{1 + \frac{PET(x)}{P(x)} - \sqrt{\left(1 + \frac{PET(x)}{P(x)}\right)^2 - 4 \times \frac{1-ETO}{PET(x)} \times \frac{PET(x)}{P(x)}}}{2}$$

where $PET(x)$ is the potential evapotranspiration for grid cell x (mm) and ETO is the reference evapotranspiration (mm).

The plant available water content is calculated as:

$$W(x) = AWC(x) \times P(x) + 1.25$$

where $AWC(x)$ is the plant available water content for grid cell x (mm) and $W(x)$ is the empirical parameter.

The water production service demand is calculated as:

$$D_{water} = pop \times x + gdp \times y$$

where pop is the population density (persons \cdot km⁻²), x is the per capita water consumption (m³ \cdot person⁻¹) including domestic, agricultural, industrial, and ecological water use, gdp is the GDP density data (10⁴ yuan \cdot km⁻²), and y is the water consumption per unit GDP (m³ \cdot 10⁴ yuan⁻¹).

2.2.2 Food Service

Food service is an important function of agricultural ecosystems. There is a significant linear relationship between crop yield and the Normalized Difference Vegetation Index (NDVI). Therefore, following the research of Liu Licheng et al., the calculations are as follows:

$$\text{Supply: } G_i = \frac{G_{sum} \times NDVI_i}{NDVI_{sum}}$$

where G_i is the allocated production of grain, meat, and milk for grid cell i (t \cdot km⁻²), G_{sum} is the total production of grain, meat, and milk in the study area, $NDVI_i$ is the NDVI value for grid cell i , and $NDVI_{sum}$ is the sum of NDVI values for all cultivated land or grassland.

Demand: $D_{food} = pop \times pcf$

where D_{food} is the food demand ($t \cdot km^{-2}$), pop is the population density, and pcf is the per capita food demand ($t \cdot person^{-1}$).

2.2.3 Carbon Sequestration Service

Carbon sequestration service captures and fixes atmospheric carbon, effectively regulating climate and representing an important regulating service in ecosystems. Following the research of Liu Licheng et al., the InVEST Carbon Storage module is used to assess carbon sequestration service supply in the Shule River Basin, with demand calculated as the product of per capita carbon emissions and population density.

The total carbon storage is calculated as:

$$C_{tot} = C_{above} + C_{below} + C_{soil} + C_{dead}$$

where C_{tot} is the total carbon storage ($t \cdot km^{-2}$), C_{above} is the aboveground biomass carbon ($t \cdot km^{-2}$), C_{below} is the belowground biomass carbon ($t \cdot km^{-2}$), C_{soil} is the soil organic carbon ($t \cdot km^{-2}$), and C_{dead} is the dead organic matter carbon ($t \cdot km^{-2}$).

The carbon sequestration service demand is calculated as:

$$D_{carbon} = pop \times pcc$$

where D_{carbon} is the carbon demand ($t \cdot km^{-2}$), pop is the population density, and pcc is the per capita carbon emission ($t \cdot person^{-1}$).

2.3 Ecosystem Service Supply-Demand Ratio

The ecosystem service supply-demand ratio (ESDR) reflects the balance between supply and demand, calculated as:

$$ESDR = \frac{S - D}{\max(S) + \max(D) \div 2}$$

where $ESDR$ is the ecosystem service supply-demand ratio, S is the supply quantity, D is the demand quantity, $\max(S)$ is the maximum supply value, and $\max(D)$ is the maximum demand value.

$ESDR > 0$ indicates supply exceeds demand, $ESDR < 0$ indicates supply is less than demand, and $ESDR = 0$ indicates supply-demand balance.

The comprehensive ecosystem service supply-demand ratio (CESDR) reflects the overall supply-demand matching status of the basin, calculated as:

$$CESDR = \frac{1}{n} \sum_{i=1}^n ESDR_i$$

where $CESDR$ is the comprehensive ecosystem service supply-demand ratio, n is the total number of ecosystem service types (three in this study), and $ESDR_i$ is the supply-demand ratio for ecosystem service type i .

2.4 Ecosystem Service Supply-Demand Spatial Matching

Bivariate local spatial autocorrelation indices (LISA) in GeoDA are used to analyze the spatial matching status of ecosystem service supply and demand, calculated as:

$$LISA_i = \frac{n}{\sum_{j=1}^n w_{ij}} \times \frac{\sum_{j=1}^n w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^n (x_i - \bar{x})^2}$$

where $LISA_i$ is the bivariate local spatial autocorrelation index for unit i , w_{ij} is the spatial weight matrix between units i and j , x_i is the attribute value of unit i , \bar{x} is the mean of all attribute values, and n is the total number of regional units.

$LISA > 0$ indicates spatial clustering of high-high or low-low values, while $LISA < 0$ indicates spatial clustering of high-low or low-high values.

3.1 Ecosystem Service Supply-Demand Distribution Pattern

Overall, the total supply of ecosystem services in the Shule River Basin exceeds total demand, though differences exist among various ecosystem services and counties (Figure 2). This is primarily caused by uneven precipitation distribution. Except for water production services, where total supply is less than total demand, both carbon sequestration and food services show total supply exceeding total demand.

The total water production service supply is $23.74 \times 10^8 \text{ m}^3$, with high-value areas mainly in Subei (South), located in the southwestern part of the basin within the Yanchiwan Nature Reserve. This area has high elevation, glacier and snow cover, relatively high annual precipitation, and low evaporation, serving as the river's source region. The total water production service demand is $28.23 \times 10^8 \text{ m}^3$, with high per-unit-area demand ($245.764 \text{ m}^3 \cdot \text{km}^{-2}$) concentrated in cultivated land distribution areas in the middle and downstream regions, as well as in Dunhuang, Guazhou, and Yumen cities. These areas have favorable water-heat conditions, large agricultural water demand, high population density, and relatively developed industry compared to other basin regions, resulting in substantial water resource demand.

The total food service supply is 9.33×10^4 t, with high per-unit-area supply ($8.089 \text{ t} \cdot \text{km}^{-2}$) concentrated in Yumen and Guazhou counties with abundant cultivated land resources in the middle and downstream regions. Subei (North) and Aksai County are dominated by bare land with poor natural conditions and low food production. The total food service demand is 1.65×10^4 t, with high per-unit-area demand ($1.435 \text{ t} \cdot \text{km}^{-2}$) distributed in urban centers of Yumen and Dunhuang with high population density, while low-demand areas are in sparsely populated regions of Subei (North), Subei (South), and Aksai County.

The total carbon sequestration service supply is 5.96×10^6 t, with high per-unit-area supply ($5175.905 \text{ t} \cdot \text{km}^{-2}$) concentrated in cultivated and forested areas with high vegetation coverage. Influenced by regional ecosystem type distribution, high-value areas are found in oasis regions along both banks of the middle and downstream river, most areas of Subei (South), and the Mazong Mountain region of Subei (North). The total carbon sequestration service demand is 1.68×10^6 t, with high per-unit-area demand ($14.633 \text{ t} \cdot \text{km}^{-2}$) concentrated in urban centers of Dunhuang, Yumen, and Guazhou with high population density and carbon demand.

[Figure 2: see original paper]

3.2 Ecosystem Service Supply-Demand Quantitative Matching Analysis

Bivariate local spatial autocorrelation analysis of ecosystem service supply and demand reveals four spatial matching types in the Shule River Basin (Figure 3): high-high spatial matching (high supply-high demand), low-low spatial matching (low supply-low demand), low-high spatial mismatch (low supply-high demand), and high-low spatial mismatch (high supply-low demand).

The water production service supply-demand spatial pattern is dominated by low-high and high-low type spatial mismatches, accounting for 7.27% and 11.77% of the basin area, respectively. Low-high mismatch areas are concentrated in Subei (South), where high elevation, glacier and snow cover, and relatively high precipitation create substantial water conservation capacity, but low population and underdeveloped agriculture result in low water demand. High-low mismatch areas are concentrated in densely populated urban areas along the middle and downstream river banks, where high water demand coupled with low precipitation and high evaporation creates supply deficits.

The carbon sequestration service supply-demand spatial pattern is dominated by low-high and high-low type spatial mismatches, accounting for 10.59% and 6.58% of the basin area, respectively. Low-high mismatch areas are sporadically distributed in Subei (North), Subei (South), and parts of Aksai County, where grassland and forest land with large grassland areas provide strong carbon sequestration capacity but low demand. High-low mismatch areas are concentrated in eastern Yumen and sporadically in Guazhou and Dunhuang, where

dense populations and industrial activities result in high carbon emissions but weak carbon sequestration capacity.

The food service supply-demand spatial pattern is dominated by low-low spatial matching (37.73% of basin area), followed by low-high spatial mismatch (6.20%) and high-high spatial matching (5.32%). Low-low matching areas are concentrated in Subei (North) and parts of Subei (South) and Aksai County, where sparse populations and bare land result in low food supply and demand. High-high matching areas align closely with high population density distributions, where substantial food demand is met by high grain production from cultivated land.

[Figure 3: see original paper]

[Figure 4: see original paper]

4 Discussion

The Shule River Basin features a typical continental arid climate with extremely low precipitation, high evaporation, predominantly bare land, and sparse population. This study analyzed supply-demand characteristics and spatial matching status of water production, carbon sequestration, and food services from a supply-demand perspective. The findings reveal that except for water production services, the other two ecosystem services show supply exceeding demand, with water production services exhibiting the most severe spatial mismatch. This is primarily related to the basin's high-south-low-north terrain and uneven precipitation distribution, consistent with previous research findings. Unlike water-heat-rich, economically developed plain areas, the Shule River Basin's ecosystem service supply and demand lag significantly due to natural and socio-economic constraints, though overall supply-demand balance is maintained. The terrain's large relief, extensive bare land, and sparse vegetation significantly influence ecosystem service supply and demand, creating large areas with low-low supply-demand patterns.

The central basin region serves as an agricultural concentration area and densely populated zone, where ecosystem service supply-demand spatial matching generally exhibits high-low spatial mismatch. For these areas, it is necessary to strengthen farmland ecological protection, restore degraded cultivated land, level fields to improve quality, enhance irrigation technology, and introduce water-saving projects for farmland transformation. Except for food services, the northern and southern regions of the study area are high-supply areas for the other two services. These vast but sparsely populated regions require enhanced protection of ecologically fragile areas, appropriate afforestation, and strict prohibition of unreasonable human disturbance.

Ecosystem services and human sustainable development share a causal relationship, with ecosystem service supply and demand representing a complex, dynamic process of ecosystem services flowing from natural ecosystems to hu-

man social systems. Current research methods for ecosystem service supply and demand primarily rely on evaluation matrices and value equivalents. This study selected three ecosystem services, quantified their supply and demand, and clarified their spatial supply-demand patterns. However, this research only selected a single year without temporal sequence analysis of supply-demand changes. Furthermore, most current research remains at the stage of analyzing spatiotemporal supply-demand characteristics, while clarifying the spatial dynamic flow process from ecosystem service supply to demand requires further investigation. Future research should analyze interannual variations in ecosystem service supply and demand over long time series, distinguish balance relationships among potential supply, actual supply, potential demand, and actual demand, and further explore ecosystem service flow mechanisms and internal mechanisms to provide theoretical support for regional ecological security and sustainable development.

5 Conclusion

This study utilized multisource data, taking the Shule River Basin as an example, and combined spatial analysis tools including InVEST, ArcGIS, and GeoDA to evaluate supply-demand characteristics of water production, carbon sequestration, and food services. The ecosystem service supply-demand matching status was analyzed, yielding the following conclusions:

1. High-value areas of water production service supply are mainly distributed in high-elevation southern regions of the Shule River Basin. High-value areas of carbon sequestration service supply are primarily distributed in the middle and downstream regions and southern areas with good vegetation cover. High-value areas of food service supply are distributed in oasis regions of the Shule River Basin. High-value areas of demand for all three services are concentrated in urban centers of Dunhuang, Guazhou, and Yumen with high population density.
2. The water production service supply-demand ratio is less than 0, indicating supply deficit, while carbon sequestration and food service supply-demand ratios exceed 0, indicating supply surplus. Overall, the ranking is carbon sequestration services > food services > water production services, though different ecosystem services vary across regions.
3. Four spatial matching types exist in the Shule River Basin: high-high spatial matching, low-low spatial matching, low-high spatial mismatch, and high-low spatial mismatch. Water production services are dominated by low-high spatial mismatch; carbon sequestration services are dominated by both low-high and high-low spatial mismatches; and food services are primarily characterized by low-low spatial matching.
4. Water production service supply surplus areas are concentrated in high-elevation Subei (South), while supply deficit areas are concentrated in densely populated, agriculturally developed middle and downstream re-

gions. Carbon sequestration service supply surplus areas are sporadically distributed in Subei (North) and Subei (South), while deficit areas are concentrated in densely populated urban centers. Food service supply surplus areas are concentrated in cultivated land-rich middle and downstream regions, with few deficit areas.

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

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