Postprint: Ecological management zoning in Northwestern China based on ecosystem services supply-demand matching

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Date: 2025-06-20T00:00:00+00:00

Abstract

Accurate identification of the spatial characteristics of ecosystem service supply and demand, along with the delineation of ecological management zones, holds significant importance for guiding regional ecosystem management and restoration. Focusing on the overall ecosystem of Northwest China and from the perspective of water-energy-food synergistic development, this study quantifies the spatial matching characteristics of water yield service, carbon sequestration service, and food supply and demand in Northwest China from 2000 to 2022, and delineates ecological management zones based on supply-demand matching surplus conditions and sustainability characteristics. The results show that: (1) The spatial matching status of supply and demand for various ecosystem services in Northwest China differs; the supply and demand of water yield and food services show a fluctuating upward trend or remain stable; the demand for carbon sequestration service increases, while both supply and the supply-demand ratio show a downward trend, leading to a gradual imbalance in supply-demand matching. (2) Food production services are mostly of the sustainable development type, while water yield services and carbon sequestration services are mostly of the unsustainable type. (3) Implementing classified management of ecological zones, balancing nature and human well-being, and enhancing ecosystem service supply. The research results can provide scientific references for the rational allocation of basic resources and precise management of ecosystem services in Northwest China.

Full Text

Preamble

ARID LAND GEOGRAPHY Vol. 48 No. 6 Jun. 2025
Static-Dynamic Matching of Ecosystem Service Supply and Demand

and Ecological Management Zoning in Northwest China

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Abstract

Accurately identifying the spatial characteristics of ecosystem service supply and demand, as well as delineating ecological management zones, is crucial for guiding regional ecosystem management and restoration efforts. This study focuses on the overall ecosystem of northwest China, quantifying the spatial matching of water production, carbon sequestration, and food services from 2000 to 2022 using the water-energy-food nexus as a framework. Ecological management zones are delineated based on the surplus and sustainable characteristics that align supply with demand. The results indicate that: (1) The spatial matching of supply and demand for ecosystem services in northwest China varies. Specifically, the supply and demand for water production and food services either fluctuate or remain stable, whereas the demand for carbon sequestration services increases. This rise in demand, coupled with declining supply and demand-supply ratios, leads to a gradual imbalance in matching supply and demand. (2) Food production services are primarily sustainable, whereas water production and carbon sequestration services tend to be unsustainable. (3) Classification and management of ecological zones that consider both ecological and human well-being are necessary, with the aim of enhancing the supply of ecosystem services. The findings of this study provide valuable scientific insights into the rational allocation of basic resources and the precise management of ecosystem services in northwest China.

Keywords: ecosystem services; supply-demand match; ecological management zoning; northwest China

Introduction

Ecosystem services represent the benefits humans derive from ecosystems and provide an important foundation for societal development [1]. The supply function of ecosystem services refers to the various products and services provided by ecosystems, while human consumption of these products and services during survival and development creates demand, reflecting the flow of ecosystem services from natural systems into the social sphere [2]. Exploring ecosystem services in the context of supply and demand is significant for achieving sustainable use of natural capital and coordinating ecosystem service supply and demand, while ecological management zoning based on supply-demand matching can provide effective references for optimizing spatial layout and improving human well-being [3]. Dynamic matching analysis can reflect historical evolution characteristics and future states of ecosystem service supply and demand [4], which is beneficial for scientific management decision-making.

Contemporary society continues to develop, and considering both the current state and future changes in ecosystem service supply-demand matching is essential for delineating ecological zones. Currently, human demand for food, water resources, and energy continues to increase, exacerbating ecosystem vulnerability and negatively impacting water, energy, and food security [5]. Coordinated management of the water-energy-food nexus and investigation of the supply-demand matching relationships among these three elements can greatly benefit regional collaborative development and management of ecosystem services [6].

Most of northwest China lies west of the "Hu Huanyong Line." The region is vast with favorable light and heat resources and abundant traditional energy reserves, but faces increasingly prominent ecological problems including water shortages, soil erosion, population growth, and economic development [7]. In the "Two Screens, Three Belts, One Area, and Multiple Points" strategic pattern for ecological security, northwest China bears an important mission [8]. Scholars have investigated ecological management in northwest China at various scales including provincial, municipal, and county levels [9], but few studies have examined the region as a whole. Therefore, this study quantifies the spatial matching characteristics of water production, carbon sequestration, and food supply and demand in northwest China from 2000 to 2020 based on the water-food nexus perspective, delineates ecological management zones according to surplus conditions and sustainable characteristics, and provides corresponding policy recommendations for ecological civilization construction in the region.

1. Materials and Methods

1.1 Study Area

Northwest China includes Shaanxi, Gansu, Ningxia, Qinghai, and Xinjiang, comprising 51 prefecture-level administrative regions (Fig. 1) with a total land area of 308$\times10^{4}$ km^2. According to the seventh national census, the total population is approximately 1.04$\times10^{8}$. Influenced by unique landforms and climatic conditions, northwest China relies primarily on irrigated agriculture, cultivating drought-resistant crops such as wheat, soybeans, highland barley, and maize. Key grain production areas include the Guanzhong Plain in Shaanxi, the Hexi Corridor in Gansu, Ningxia, and southern Xinjiang [10]. As a critical region for the "Western Development" strategy and "Belt and Road" initiative, northwest China also occupies an important position in China's energy strategic layout.

1.2 Data Sources

This study utilizes multi-source datasets to quantify and characterize the spatial distribution of ecosystem service supply and demand (Table 1). All data were resampled to a 500 m spatial resolution and projected using the WGS_{{{1984}}}_{{Albers}} coordinate system for data preprocessing, spatial analysis, and statistics in ArcGIS 10.8.

Table 1 Data sources | Data Type | Resolution | Source | |——-|———|—-- | | Land use data | 500 m | China Land Use Dataset (1980-2020) published by Professors Yang Jie and Huang Xin | | NDVI | 500 m | MOD13A3 | | Nighttime light data | 500 m | https://search.earthdata.nasa.gov/search | | DEM | 500 m | GEBCO (http://www.gebco.net/) | | Soil data | 500 m | https://zenodo.org/records/8176941 | | Population density | 1 km | LandScan (https://landscan.ornl.gov) | | Socioeconomic data | - | Statistical yearbooks, water resources bulletins, China Energy Statistical Yearbook |

1.3 Quantification of Ecosystem Services

1.3.1 Water Production Service **Water Yield.** The InVEST model' s water yield module was used to assess annual water production in northwest China, calculated as follows:

$$P(x)_i = P(x) - AET(x)_i$$

where $P(x)_i$ is the annual water yield in grid cell x for land use type i (mm); $P(x)$ is the precipitation in grid cell x (mm); and $AET(x)_i$ is the actual annual evapotranspiration in grid cell x for land use type i (mm).

Water Demand. Water demand includes agricultural, industrial, residential, and ecological components. Industrial water use was allocated based on secondary industry output, residential water use was distributed according to population density data, and agricultural and ecological water uses were allocated based on cultivated land and green space types in the land use data. The four water use types were superimposed to obtain total water demand in northwest China [11]. The formula is:

$$D_{water} = D_{agr} + D_{eco} + D_{ind} + D_{gdp}$$

where D_{water} is annual water demand ($m^3 \cdot km^{-2}$); D_{agr} is agricultural water use ($m^3 \cdot km^{-2}$); D_{eco} is ecological water use ($m^3 \cdot km^{-2}$); D_{ind} is industrial water use ($m^3 \cdot km^{-2}$); and D_{gdp} is domestic water use ($m^3 \cdot km^{-2}$).

1.3.2 Carbon Sequestration Service Carbon storage refers to the total amount of carbon accumulated and stored in natural ecosystems through biochemical processes during a specific period [12]. Human production activities have caused carbon emissions to rise continuously, posing increasingly severe global environmental challenges. Balancing carbon emissions with carbon storage requires enhancing ecosystem carbon storage capacity while reducing socioeconomic carbon emissions to achieve the "dual carbon" goals.

Carbon Storage. The InVEST model was used to calculate carbon storage as follows:

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

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

Carbon Demand. Recent studies have verified the relationship between nighttime light data and carbon emissions, widely applying such data to investigate spatiotemporal patterns of carbon emissions [13]. Modified nighttime light data were used to reflect the spatial distribution of carbon emissions, calculated as:

$$CD_j = \frac{DN_j}{DN_{sum}} \times C_{sum}$$

where CD_j is carbon storage demand in grid cell j ($t \cdot hm^{-2}$); DN_j is the nighttime light brightness value in grid cell j; DN_{sum} is the total nighttime light brightness value in the study area; and C_{sum} is the total carbon emissions in the study area ($t \cdot hm^{-2}$).

1.3.3 Food Service Food Production. Using NDVI to measure food production capacity is an important method for calculating food production. This study used the ratio of grid cell NDVI values to total NDVI values in cultivated land as a coefficient for food production, calculated as:

$$FP(x) = \frac{NDVI(x)}{NDVI_{sum}} \times F_{sum}$$

where $FP(x)$ is food production in grid cell x ($t \cdot hm^{-2}$); $NDVI(x)$ is the NDVI value in grid cell x; $NDVI_{sum}$ is the total NDVI value in cultivated land types; and F_{sum} is the actual total food production in northwest China ($t \cdot hm^{-2}$).

Food Demand. Food demand was calculated as the product of per capita food consumption and population density [14]:

$$D_{food} = D_{pop} \times W_{food}$$

where D_{food} is food service demand ($t \cdot hm^{-2}$); D_{pop} is population density in the grid cell ($persons \cdot km^{-2}$); and W_{food} is per capita food consumption ($t \cdot person^{-1}$).

1.4 Supply-Demand Matching Analysis

1.4.1 Static Matching The ecosystem service supply-demand index (SDI_x) links ecosystem service supply and demand to reflect surplus, balance, or deficit conditions in different regions [15], calculated as:

$$SDI_x = \frac{ESS_x - ESD_x}{ESS_x + ESD_x}$$

where ESS_x is the ecosystem service supply in region x; and ESD_x is the ecosystem service demand in region x. Based on matching conditions, the study area was divided into surplus zones (supply > demand), balance zones (supply demand), and deficit zones (supply < demand).

1.4.2 Dynamic Matching Static matching represents the matching status at a specific moment but cannot capture sustainable characteristics. Therefore, dynamic matching analysis was introduced to characterize sustainability based on the intensity of change in ecosystem service supply and demand [16]:

$$\Delta ESS = \frac{ESS_b - ESS_a}{ESS_a}, \quad \Delta ESD = \frac{ESD_b - ESD_a}{ESD_a}$$

where ΔESS and ΔESD represent changes in ecosystem service supply and demand, respectively; ESS_a and ESS_b are supply in years a and b; and ESD_a and ESD_b are demand in years a and b.

Using supply and demand change intensity as coordinate axes, space was divided into four quadrants based on the signs of ΔESS and ΔESD, with the balance line of incremental changes as the boundary. By comparing the absolute values of ΔESS and ΔESD, types were classified as follows (Fig. 2):

- **Sustainable types**: Supply growth > demand growth; Supply increase and demand decrease; Supply decrease < demand decrease
- **Unsustainable types**: Supply growth < demand growth; Supply decrease > demand decrease; Supply decrease and demand increase

1.5 Ecological Management Zoning

Following previous research [17], static matching was used to indicate ecosystem service surplus or deficit, while dynamic matching indicated sustainability. The study delineated four ecological management zones (Fig. 2):

1. **Ecosystem Surplus Sustainable (S-S)**: Supply exceeds demand or is relatively balanced, with the supply-demand gap gradually increasing or remaining stable.
2. **Ecosystem Surplus Unsustainable (S-US)**: Supply exceeds demand or is relatively balanced, but the supply-demand gap is gradually narrowing.

3. **Ecosystem Deficit Sustainable (D-S)**: Supply is less than demand, but the gap is gradually narrowing.
4. **Ecosystem Deficit Unsustainable (D-US)**: Supply is less than demand, and the gap is gradually increasing.

2. Results

2.1 Historical Evolution of Ecosystem Service Supply and Demand in Northwest China

Northwest China’ s ecosystem services showed different supply-demand trends from 2000 to 2020 (Table 2). To eliminate climate fluctuation effects and better reflect current conditions, 2020 data were used as the average of 2015-2020 data (the same applies below). Overall, all three ecosystem service supply-demand indices were positive, indicating that the water-food system in northwest China is generally coordinated. However, the carbon sequestration service index declined annually, decreasing from 0.16 in 2000 to 0.10 in 2020, presenting a potential threat of supply-demand imbalance.

Table 2 Evolution of supply and demand of ecosystem services in northwest China from 2000 to 2020

Service	2000	2010	2020	Change Trend
Water yield supply ($m^3 \cdot hm^{-2}$)	656.86	815.37	815.37	↑
Water demand ($m^3 \cdot hm^{-2}$)	39.86	260.78	282.17	↑
Carbon storage ($t \cdot hm^{-2}$)	39.33	39.33	39.33	→
Carbon demand ($t \cdot hm^{-2}$)	0.10	0.13	0.16	↑
Food production ($t \cdot hm^{-2}$)	0.16	0.16	0.16	→
Food demand ($t \cdot hm^{-2}$)	0.10	0.10	0.10	→

Water yield and food production supplies showed increasing trends, with water yield increasing from 656.86 $m^3 \cdot hm^{-2}$ to 815.37 $m^3 \cdot hm^{-2}$ and food production remaining stable at 0.16 $t \cdot hm^{-2}$. In contrast, carbon storage supply fluctuated, increasing from 39.33 $t \cdot hm^{-2}$ to 39.86 $t \cdot hm^{-2}$. Demand for water increased from 39.86 $m^3 \cdot hm^{-2}$ to 282.17 $m^3 \cdot hm^{-2}$, while carbon emissions continued to increase, primarily due to local economic development and population growth, leading to a gradually imbalanced supply-demand relationship.

2.2 Spatial Characteristics of Ecosystem Services

2.2.1 Supply Characteristics The three ecosystem services showed distinct spatial distribution patterns (Fig. 3). Water yield was distributed roughly along northwest-southeast axes, decreasing from these axes toward surrounding areas and from mountains to basins, influenced by geography, topography, and weather systems. The Sanjiangyuan area, known as the “Chinese Water Tower,” is an important water source replenishment zone. Water yield in southern Gansu, southern Ningxia, and northern Shaanxi increased annually.

Changes in terrestrial ecosystem carbon storage are mainly caused by land use type changes [18]. Cultivated land, forestland, and wetlands are high-value carbon storage areas, while glaciers, construction land, and bare land have low carbon storage. Food production correlates with cultivated land distribution, with high-value production areas concentrated in suitable agricultural regions such as the Ningxia Plain, Weihe Plain, Hexi Corridor in Gansu, and Tarim River Basin.

2.2.2 Demand Characteristics Ecosystem service demand is concentrated in densely populated areas with prominent social activities (Fig. 4). Water demand high-value areas are in central Shaanxi, particularly significant. During the study period, water demand in Xinjiang increased annually. With economic growth, industrial restructuring, and urbanization, carbon emissions continued to rise, showing a "high at both ends, low in the middle" distribution pattern that increased annually. High carbon demand values in the east concentrated in the Ningxia Plain, Guanzhong Plain, and Loess Plateau, while western high values concentrated near the Tarim and Junggar Basins. Food demand high-value areas first decreased then stabilized, notably in the Guanzhong Plain of central Shaanxi.

2.3 Static Matching Spatial Characteristics

For water production, high supply-demand index areas showed a "high at both ends, low in the middle" pattern (Fig. 5). The Sanjiangyuan area, upper Yellow River reaches, and Tianshan-Altai Mountains have abundant water resources. Most areas in northern Gansu, northern Ningxia, and Xinjiang face water imbalance due to arid and semi-arid conditions with low precipitation and high agricultural irrigation demand.

Carbon sequestration had the highest index among the three services, indicating carbon sink advantages in northwest China. The spatial pattern showed point and band distributions, with deficit areas gradually converting to balance zones in central and western regions during 2010-2015. However, deficit ranges expanded from 2015-2020, and continued carbon emissions growth is unfavorable for carbon balance and "dual carbon" goal achievement.

Food service high-value areas aligned with cultivated land distribution, concentrated in irrigation areas along the Guanzhong Plain, Ningxia Plain, and Xinjiang river lines. Large low-value areas appeared in 2000 due to limited agricultural technology and fragile ecological conditions. Eastern region food supply-demand imbalance persisted throughout the study period.

2.4 Dynamic Matching Spatial Characteristics

Dynamic matching reveals future development trends (Fig. 6). For water production, central-eastern regions generally had good water resource bases with dynamic matching types of SIDI-S, but water supply growth lags behind demand growth, potentially facing structural water shortages in the future. Southwestern Xinjiang, central Shaanxi, and northern Ningxia showed D-S types, where supply-demand contradictions are easing.

For carbon sequestration, most regions had carbon storage growth less than carbon emission growth, indicating potential future imbalance. However, western Xinjiang, Zhangye and Linxia in Gansu, Weinan in Shaanxi, and most of Ningxia (except Guyuan) showed SIDI-S types, where carbon storage growth exceeds emission growth.

Food production services were primarily sustainable (SIDI-S) across northwest China. Unsustainable types (SIDI-US) occurred in Urumqi (Xinjiang) and western Shaanxi, where food supply growth is less than demand growth due to dense populations. SDDD-US types appeared in Ankang, Shangluo, and Yulin (Shaanxi), Xining and Yushu (Qinghai), Lanzhou (Gansu), and Alar (Xinjiang), where both supply and demand are decreasing but supply is declining faster, potentially creating food security issues.

2.5 Ecological Management Zoning

Combining static and dynamic matching identified four ecological management zones (Fig. 7):

1. **S-S type**: Scattered across all services. Weinan City in Shaanxi had supply exceeding demand or balanced conditions across all three service types, indicating excellent ecosystem services. Tacheng region also showed good conditions for carbon sequestration and food services.
2. **S-US type**: Concentrated in water and carbon sequestration services. Water services mainly involved eastern northwest regions, while carbon sequestration involved most of the region. This zone has supply-demand gaps gradually narrowing, potentially leading to future supply shortages.
3. **D-S type**: Mainly distributed in food services, and some water and carbon sequestration services. The supply-demand gap is gradually narrowing, requiring improved water use efficiency, construction of interconnected water cycling systems, and enhanced natural ecosystem carbon sinks.
4. **D-US type**: Primarily in water production services, with some distribution in food services. Xinjiang' s Karamay, Urumqi, and Jiayuguan in Gansu frequently showed this type, where ecosystem service supply is decreasing while demand increases. This zone requires strengthened ecosystem service management and optimization.

3. Discussion

3.1 Ecosystem Service Supply-Demand and Spatial Matching Relationships

Effective ecosystem service supply-demand management strategies can achieve "win-win" outcomes across services. Compared with previous studies, integrating supply-demand matching trends with sustainable development characteristics provides a more comprehensive reflection of current conditions and future dynamics, enabling more precise and effective ecological management strategies [19].

In the coordinated development of the water-food nexus, water resources occupy a core position. Regional collaborative management must be "water-based and water-measured," following local characteristics to rationally plan food and energy industry layouts [20]. Resource-based and structural water shortages remain important constraints on social development and ecological improvement in northwest China [21]. Food service supply increases benefit from ecosystem structural adjustments and agricultural technological progress, while food demand remains relatively stable, related to local population structure and lifestyle.

For carbon sequestration services, grassland degradation was the main cause of carbon storage changes in northwest China from 2000-2020 [22]. Construction land development and cultivated land expansion during the "Belt and Road" process have led to significant carbon emission increases. While promoting economic development, northwest China must attach great importance to carbon emission reduction and ecological restoration to gradually achieve carbon cycle balance.

3.2 Management Strategies for Different Zones

To better integrate into the new development pattern, northwest China must balance development and protection, focusing on "dual carbon" goals to comprehensively promote coordinated green development of economy, society, and ecology. Specific regulation strategies are needed for different ecological management zones:

S-S zones: Mostly distributed near river lines or piedmont basins as core ecological areas. These are key protection zones for ecosystem service supply in northwest China. Strategies should improve ecological resource use efficiency, accelerate development of green low-carbon circular economic systems, and cultivate resource-saving and environment-friendly production and lifestyles [23].

S-US zones: Mainly involve water production services. These zones have imbalanced ecosystem services that are continuously deteriorating. Strategies must optimize land use and industrial structures, comprehensively promote integrated protection and management of mountains, rivers, forests, farmlands, lakes, grasslands, sand, and ice, and establish cross-regional ecological compensation mechanisms [24].

D-S zones: Involve food and carbon sequestration services. The narrowing supply-demand gap may lead to future shortages. Strategies should improve water resource utilization efficiency, construct modern water cycling systems, and enhance natural ecosystem carbon sinks to coordinate high-quality development with ecological protection [25].

D-US zones: Characterized by food services, these zones have supply-demand gaps gradually expanding. Strategies must ensure cultivated land security, coordinate production, living, and ecological space layouts, and gradually construct agricultural and ecological spatial layouts that meet market demands and habitat quality requirements [26].

4. Conclusion

1. **Temporal trends**: Water production supply and demand both showed fluctuating increases, with supply growth exceeding demand growth. Food production supply increased while demand stabilized, with the supply-demand index growing annually. Carbon demand increased while carbon storage and the carbon sequestration supply-demand index decreased, affecting future carbon balance and "dual carbon" goal achievement.
2. **Spatial characteristics**: Under static matching, water production showed an "east-west high, middle low" pattern, with deficit ranges expanding in northern Xinjiang. Carbon sequestration generally had supply exceeding demand, but deficit areas increased annually, aligning with carbon emission distribution. Food production deficit ranges decreased, with low-value areas concentrated in southern and northwestern regions. Under dynamic matching, food services were mostly sustainable, while carbon sequestration and water production were mostly unsustainable, facing risks of local imbalance between ecological carrying capacity and social development.
3. **Municipal-scale management zoning**: Water production services were mostly unsustainable, making water resources a constraint on future sustainable development. Carbon sequestration services primarily involved D-S and S-US types, requiring enhanced carbon sinks to promote carbon balance. Food services were mainly sustainable, with D-US types scattered in southern, eastern, and northern areas, requiring continued cultivated land security and coordinated spatial layouts.

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