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Matching Supply and Demand of Ecosystem Services in the "Mountain-Oasis-Desert" System: A Case Study of the Heihe River Basin

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Abstract

The Heihe River Basin was selected as the study area in this paper. Based on spatial and statistical data, the InVEST model and related formulas were used to quantify the supply and demand of four ecosystem services: Water Yield (WY), Soil Retention (SR), Carbon Sequestration (CS), and Food Production (FD). Using these results, the supply-demand ratio and Z-score standardization were applied to analyze the matching of supply and demand for ecosystem services in the basin. Finally, the driving factors affecting the ecosystem service supply-demand ratio were explored by using Geo Detector. The results indicated that: (1) The spatial pattern of ecosystem service supply and demand in the Heihe River Basin exhibited significant gradient differentiation and spatial heterogeneity. Overall, the total supply of three ecosystem services: Soil Retention (SR), Carbon Sequestration (CS), and Food Production (FD) exceeded their total demand; in contrast, the total supply of Water Yield (WY) services fell short of demand. (2) The supply and demand of ecosystem services in the basin exhibit a spatial gradient pattern of "mountain surplus - oasis balance - desert deficit". The mountain subsystem is dominated by high supply-low demand(H-L) and high supply-high demand(H-H) matching types; in contrast, in contrast, the oasis subsystem features mixed-type matches, and the desert subsystem is characterized by low supply-low demand (L-L) matching types. (3) The supply-demand ratios of ecosystem services in the Heihe River Basin are primarily influenced by socio-economic factors such as population density (POP) and GDP.

Keywords

"Mountain-oasis-desert" System; Matching Supply and Demand of Ecosystem Services; Driving Factors; Heihe River Basin.

1. Introduction

Ecosystem services, as the multiple benefits that humans derive directly or indirectly from ecosystems, encompass the complex processes by which natural ecosystems deliver material and energy to socio-economic systems, consume and transform wastes generated by socio-economic activities, and provide various types of service resources to humans (Fan et al.,2020; Jiang et al.,2021). In recent years, the imbalance between the supply of and demand for ecosystem services has become increasingly serious, accompanied by the intensification of global climate change and the continued rise in the intensity of human activities. According to the United Nations Millennium Ecosystem Assessment, about 60 per cent of global ecosystem services are facing degradation and unsustainable use, a trend that not only poses a serious threat to human well-being, but also poses a potential risk to regional and global ecological security (Jia et al.,2023). How to scientifically plan and efficiently manage ecosystem services and achieve synergy between ecological protection and socio-economic development has become a key proposition for regional sustainable development and ecological civilization construction (Bratman et al.,2019). The assessment of the supply of and demand for ecosystem services has become a necessary prerequisite to support ecosystem science management and decision-making (Zhao et al.,2021; Chen et al.,2024). Ecosystem service provision refers to the various types of resources and services provided by ecosystems to human society (Burkhard et al.,2012), while service demand reflects the process of human consumption and utilization of ecosystem outputs. The dynamic interaction of supply and demand together builds a flow system of ecosystem services from natural ecosystems to human social systems (Ma et al.,2017).

Research on the synergy between supply and demand of ecosystem services has become a cutting-edge hotspot in the field of resource management (Lin et al.,2024). The research paradigm has gradually evolved from a single ecosystem service assessment to a comprehensive consideration of supply and demand; the research content has also expanded from a simple quantitative analysis of regional supply and demand to dimensions such as supply and demand matching assessment, risk assessment and spatial zoning planning (Zhang et al.,2021). At the research methodology level, the degree of matching supply and demand of ecosystem services is a key indicator of the potential for coordinated development of socio-economic systems and natural ecosystems (Chen et al.,2024). Currently, quantitative assessment systems for ecosystem service provision are relatively mature, covering the value assessment method (Costanza et al., 1997), expert assessment method (Burkhard et al.,2015), and model assessment method (Yin et al.,2021). Among them, the InVEST model, the MIMES model, the KINEROS hydrological model, and the SolVES model are among the models that are widely used in quantitative supply assessment. In contrast, quantitative assessment of the demand for ecosystem services has not yet been standardized (Shen et al.,2021). Studies on the driving mechanisms of ecosystem services have focused on natural elements such as climatic conditions, land use types, topography and soil properties, and socio-economic factors such as population distribution, level of economic development, and policy regulation (Hauck et al.,2015). Commonly used research methods include geographically weighted regression (GWR) models (Liu et al.,2022), spatial error and spatial lag models (Sannigrahi et al.,2020), redundancy analysis (Feng et al.,2017), and multiple stepwise regression analysis (Hao et al.,2017). The research scale has been gradually expanded from county and township level micro-units to municipal, provincial, watershed, urban agglomeration, and even nationwide (Liu et al.,2020; Han et al.,2021; Gao et al.,2023; Gai et al.,2025; An et al.,2024; Su et al.,2024), focusing on the spatial and temporal evolution of ecosystem service supply and demand relationships, and the practical implications of supply and demand matching studies for ecological management. However, limited by the difficulty of data acquisition and the constraints of research methodology, most of the existing studies focus on the evaluation of the level of ecosystem service provisioning, and the systematic research on the matching status of supply and demand is still insufficient (Dong et al.,2018); There is no harmonized standard on the methodology for quantifying requirements. Much of the focus is on the static matching of supply and demand within the subsystems of the basin, without considering the process of flow from areas of supply where there is an oversupply of services to areas of demand where there is a demand for services as a result of spatial mismatches. In addition, there are no systematic cases that can comprehensively explain how to achieve the organic unity of ecological, economic and social benefits through scientific spatial pattern optimization at the watershed scale, and then promote the ecological environmental protection and sustainable development of watersheds (Sun et al.,2023).

As a complex and highly coupled ecosystem, the "mountain-oasis-desert" system is an important part of the regional ecological environment and plays an irreplaceable role in maintaining biodiversity, regulating the regional climate and guaranteeing water security. The Heihe River Basin is subject to the integrated control of the Tibetan Plateau and the continental hinterland, and the basin has formed a "chain-like mountain-patch oasis-widespread desert" ecosystem from the southeast to the northwest, with obvious ecological gradients and clear system boundaries(Wang et al.,2017), and the basin's unique geographic pattern and ecological environment have made it the best choice for ecological governance and water resource management, This unique geographic pattern and ecological environment of the watershed make it of special importance in ecological governance, water resources management, biodiversity conservation, economic development and policy formulation.

Current research on the supply and demand of ecosystem system services in the Heihe River Basin mainly focuses on single services and specific areas such as the upper and middle reaches, and lacks research on the basin as a whole, multiple services, and driving mechanisms. Therefore, taking the Heihe River Basin as an example, this paper carries out a study on the matching characteristics of the supply and demand of WY, SR, CS, FD and other services and the driving mechanism of the Heihe River Basin's "mountain-oasis-desert" system, which will help to accurately identify the ecosystem service background state and provide a basis for the "mountain-oasis-desert" system to be more efficiently and effectively utilized. It will provide theoretical support and practical guidance for the scientific management and sustainable development of the "mountain-oasis-desert" system.

2. Study Region and Data Sources

2.1. Study Region

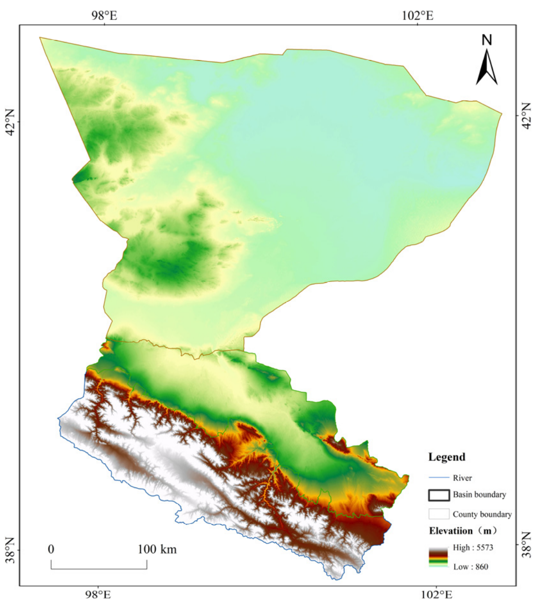

Fig 1. Location of the Heihe River Basin

The Heihe River Basin (37.1°N~42.7°N, 97.1°E~103.0°E) is the second largest inland river basin in Northwest China, located in the Qilian Mountains and the middle part of the Hexi Corridor, flowing through the provinces of Qinghai, Gansu, and the Inner Mongolia Autonomous Region, and ultimately merging into the Juyenhai Sea, with a total length of 821 km, and a watershed area of 143,000 km^2. The basin has a typical continental arid climate, rich in light and heat resources, with an average annual temperature of 6~10°C, a dry climate, and an annual precipitation of 40~500mm, which is scarce and concentrated. The terrain in the basin is undulating, high in the south and low in the north, with large differences in geomorphology and landscape, with obvious horizontal and vertical differentiation, forming an ecosystem of "chained mountains - patchy oasis - extensive desert" from the southeast to the northwest (Wang et al.,2017). In recent years, under the dual role of natural and man-made factors, all ecosystem services in the watershed have declined or degraded to varying degrees, which has affected the local socio-economic development and threatened the ecological and environmental security of the watershed.

2.2. Data Sources

The basic data used in this paper include: administrative boundary data, river data, land use data, digital elevation model, precipitation data, evapotranspiration data, available water content of vegetation, rooting depth data, Normalized Vegetation Index (NVI), population density data, food production and consumption data, water demand and consumption data, and carbon emissions, with sources of data as shown in Table 1.

Table 1. Sources of data for the study

Data type	Spatial resolution	Data format	Data source
Digital Elevation Model	30m	Raster data	https://www.gscloud.cn/
Land use	30m	Raster data	http://www.ncdc.ac.cn/
Precipitation	1km	Raster data	https://data.tpdc.ac.cn/
Evapotranspiration	1km	Raster data	https://data.tpdc.ac.cn/
Soil data	-	Raster data	https://data.tpdc.ac.cn/
Normalized difference vegetation index	1km	Raster data	https://www.earthdata.nasa.gov/
Root restricting layer depth	1km	Raster data	https://doi.org/10.1038/s41597-019-0345-6(Yan et al.,2020)
Administrative boundaries	-	Vector data	https://www.resdc.cn/
River data	-	Vector data	https://www.webmap.cn/
Population density	1km	Raster data	https://landscan.ornl.gov
Gross Domestic Product intensity data	1km	Raster data	https://www.resdc.cn/
Food production	-	Statistical data	2022 Yearbook of provinces, cities and counties in the study area
Food demand	-	Statistical data	China Household Survey Yearbook 2022
Water demand consumption	-	Statistical data	Water Resources Bulletin 2022 for the provinces and municipalities in the study area
Carbon emission	-	Statistical data	http://www.cityghg.com/

3. Research Methods

3.1. Classification of Composite System Types

Using the townships of the study area as the basic unit, the relative dominance index was applied to classify the ecosystem type to which each township belongs.Its specific calculation formula is as follows (Yao et al.,2022):

$$D = \frac{A_{ik}/A_{ir}}{A_k/A_r} \tag{1}$$

Where, D is the index of comparative advantage; A_{ik} is k townships i functional land area; A_{ir} is Heihe River Basin i functional land area; A_k is k township area; A_r is total area of the Heihe River Basin. Larger D values indicate that the Township has an advantage in this functional land use category relative to the entire Heihe River Watershed in this category. The composite system of "mountain-oasis-desert" in the Heihe River Basin was divided into three subsystems: mountain, oasis and desert, and the classification results are shown in Fig. 2.

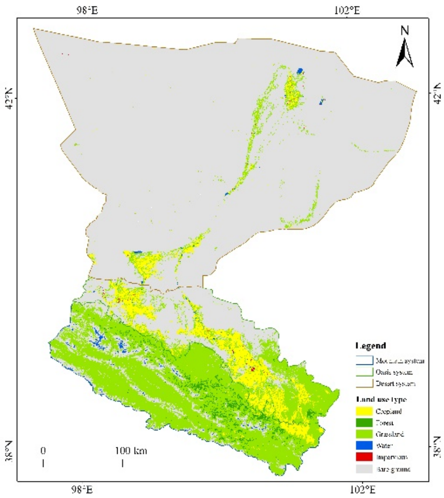

Fig 2. Boundary delineation of mountain, oasis and desert systems in the Heihe River Basin

3.2. Supply and Demand Assessment of Ecosystem Services

3.2.1. Water Yield

The water yield module (Water yield) in the InVEST model was used to calculate the supply of water yield services in the Heihe River Basin, which is based on the principle of the water cycle, with reference to a number of parameters such as precipitation, plant evapotranspiration, surface evapotranspiration, and land use, and calculates the amount of water produced by each image element, including surface runoff, water contained in the soil, and water retained on the surface(Guan et al.,2024) . Water demand in this study includes total agricultural, industrial, and domestic water use, and is estimated in the basin based on the sum of the product of population density and per capita water consumption, the product of GDP density and GDP water consumption, and the product of cultivated land area and average irrigation water use (Zhou et al.,2023).

The calculation was as follows:

Quantity supplied:

$$WY(x_i) = \left(1 - \frac{AET(x_i)}{P(x)}\right) \times P(x) \quad (2)$$

Where, $WY(x_i)$ is annual water yield on grid x for land-use type i, (mm); $AET(x_i)$ is Actual annual evapotranspiration on grid x for land-use types i, (mm); $P(x)$ is annual precipitation in for grid cell x, (mm).

Quantity demanded:

$$WYD = P_i \times DW + G_i \times DG + A_f \times DF \quad (3)$$

Where, WYD is demand for WY; P_i is raster population density(people/km^2); DW is water consumption per capita(people/m^3); G_i is raster GDP density(10^{4}yuan/ km^2); DG is water consumption per 10,000 yuan of GDP(m^3); A_f is cropland area(hm^2); DF is average irrigation water use for arable land(m^3/ hm^2).

3.2.2. Soil Retention

The sediment delivery ratio (SDR) model in the InVEST model was used to calculate the supply of soil conservation services in the Heihe River Basin, using the digital elevation model, rainfall erosion factor, soil erodibility factor, land use, vegetation cover, and soil and water conservation measure factor as input parameters. Use the actual soil conservation USLE as the demand for soil conservation services. Actual soil erosion is the amount of ecosystem services that humans expect to be able to be treated and expect to receive (Zhang et al.,2021).

Quantity supplied: (Shi et al.,2024):

$$SC = RKLS - USLE \quad (4)$$

$$RKLS = R \times K \times LS \quad (5)$$

$$USLE = R \times K \times LS \times C \times P \quad (6)$$

Where, SC is Soil retention; $RKLS$ is potential soil conservation (t); $USLE$ is actual soil retention(t); R is rainfall erosivity factor; K is soil erodibility factor; LS is slope factor; C is vegetation cover factor; P is soil and water conservation factors.

Quantity demanded is (6).

3.2.3. Carbon Sequestration

Supply is calculated by using the Carbon Storage and Sequestration module (Carbon Storage) of the InVEST model to calculate the supply of carbon sequestration services in the Heihe River Basin, which divides ecosystem carbon stocks into four basic carbon pools: above-ground biogenic carbo, below-ground biogenic carbon, soil organic carbon, and dead organic carbon. Land use and carbon pool were used as input parameters to calculate the supply of carbon sequestration services in the Heihe River Basin (Dang et al.,2024). The demand for carbon sequestration services is obtained by multiplying the per capita carbon emissions with the population density, and the carbon emissions mainly come from carbon dioxide emissions from agriculture, industry, service industry, residential life, transportation, energy consumption, and so on.

Quantity supplied:

$$C_{tot} = C_a + C_b + C_s + C_d \quad (7)$$

Where, C_{tot} is carbon sequestration(t/hm^2); C_a is above-ground biogenic carbon; C_b is below-ground biogenic carbon; C_s is soil organic carbon volume; C_d is amount of dead organic carbon.

Quantity demanded:

$$CSD = P_i \times DC \quad (8)$$

Where, CSD is demand for carbon sequestration services(t/hm^2); P_i is raster population density(people/km^2); DC is carbon emissions per capita(t/people).

3.2.4. Food Production

In accordance with the existing studies, it has been shown that there is a significant linear relationship between crops and Normalized Vegetation Index (NDVI), so in this paper, the NDVI value was used to allocate the total food quantity and calculate the supply of food services in the Heihe River Basin (Du et al.,2023). Demand for food services was obtained by multiplying per capita food consumption with population density.

Quantity supplied (Zhang et al.,2024):

$$FS = \frac{NDVI(x)}{NDVI_{sum}} \times F_{sum} \quad (9)$$

Where, FS is food production(t/hm^2); $NDVI(x)$ is NDVI values for cropland raster unit x; $NDVI_{sum}$ is total NDVI values for cropland; F_{sum} is total grain output(t).

Quantity demanded:

$$FD = P_i \times DF \quad (10)$$

Where, FD is food production(t/hm^2); P_i is raster population density(people /km^2); DF is food consumption per capita(t/people).

3.3. Supply/Demand Ratio for Ecosystem Services

The supply-demand ratio index can quantitatively represent the balance or imbalance between supply and demand for ecosystem services.

The calculation was as follows (Tao et al.,2024):

$$ESDR = \frac{S-D}{(S_{max}+D_{max})/2} \quad (11)$$

Where, ESDR is supply/demand ratio for ecosystem services; S is provisioning of various ecosystem services; D is demand for ecosystem services; S_{max} and D_{max} are maximum supply and maximum demand for each ecosystem service in the evaluation unit; ESDR>0 means that supply of an ecosystem service exceeds demand. ESDR=0 means that supply equals demand. ESDR<0 means that supply is less than demand.

The combined supply-demand ratio of ecosystem services can reflect the overall situation of matching supply and demand of ecosystem services in the study area.

The calculation was as follows:

$$\mathrm{CESDR}=\frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}}\mathrm{ESDR}_{\mathrm{i}} \tag{12}$$

Where, CESDR is the combined supply-demand ratio of ecosystem services; n is the total number of ecosystem service types, $\mathrm{ESDR_i}$ is Supply/demand ratio for ecosystem services.

3.4. Match between Ecosystem Supply and Demand

In the study of matching supply and demand of ecosystem services, the Z-core standardization method is able to compare the matching and mismatching relationships between supply and demand, Z-core standardization of ecosystem service supply and demand results, classifying the supply and demand on each raster as positive and negative, and then dividing the standardized supply as the x-axis and the demand as the y-axis into four quadrants, distinguishing the relative highs and lows of the supply and demand into four kinds of types: high supply-high demand(H-H) in the first quadrant, low supply-high demand(L-H) in the second quadrant, low supply-low demand(L-L) in the third quadrant, and high supply-low demand(H-L) in the fourth quadrant.

The calculation was as follows (Tao et al.,2024):

$$x=\frac{x_i-\bar{x}}{s} \tag{13}$$

$$\bar{x}=\frac{1}{n}\sum_{i=1}^{n}x_i \tag{14}$$

$$s=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(x-\bar{x})} \tag{15}$$

Where, x is he amount of ecosystem service supply, demand after standardization; x_i is i the unit's ecosystem service supply, demand; $\bar{x}$ is the average supply, demand of the watershed; s means the standard deviation of supply, demand for the entire watershed.

3.5. Geo Detector

This paper explores the factors influencing the supply-demand relationship of ecosystem services in the "mountain-oasis-desert" system by means of a Geo Detector. Geo Detector are mainly used to study the spatial heterogeneity of impact factors and reveal the driving forces behind them (Wang et al.,2017), and the models include: factor detection, interaction detection, ecological detection, and risk detection. In this paper, we mainly use factor detection and interaction detection to explore the degree of influence of single factors and multiple factors on the ratio of ecosystem service supply and demand in the Heihe River Basin.

(1) Factor detection: mainly applied to detect the extent to which the influence factor X explains the spatial divergence of attribute Y.

The calculation was as follows

$$q=1-\frac{\sum_{h=1}^{L}N_h\sigma_h^2}{N\sigma^2} \tag{16}$$

Where, h=1,..., upper case L is the categorization or partitioning of variable Y or factor X; N_h and $N$are the number of cells in the layer h and the whole district, respectively; σ_h^2 and $\sigma^2$are the variances of the Y values for layer h and the whole region, respectively. q is the explanatory power of the influence factor X on the attribute Y. It takes the value [0,1], and a larger value indicates a stronger explanatory power of the influence factor X.

(2) Interaction detection: This is mainly applied to assess whether the explanatory power of the dependent variable is increased or weakened by the combined effect of the influencing

factors. The method of assessment is firstly to calculate the q-values q(X1) and q(X2) of the two factors X1 and X2 on Y respectively, and to calculate the q-value q(X1∩X2) when they interact, and to compare the two results. The interaction relationship and judgment are shown in Table 2.

Table 2. Interaction type judgment

Standard of judgment	Interaction
$q(X1 \cap X2) < \min(q(X1), q(X2))$	Nonlinear weakening
$\min(q(X1), q(X2) < q(X1 \cap X2)\max(q(X1), q(X2))$	Single-factor nonlinear attenuation
$q(X1 \cap X2) > \max(q(X1), q(X2))$	Two-factor enhancement
$q(X1 \cap X2) = q(X1) + q(X2)$	Independence
$q(X1 \cap X2) > q(X1) + q(X2)$	Nonlinear enhancement

4. Analysis of Results

4.1. Patterns of Distribution of Supply and Demand of Ecosystem Services in The "Mountain-Oasis-Desert" Ecosystem

The supply and demand pattern of ecosystem services in the Heihe River Basin in 2022 was analyzed through the InVEST model and the quantitative formula for the supply and demand of related services using ArcGIS 10.4 (Fig. 3 and Table 3). From the supply side, the supply of various ecosystem services showed significant spatial heterogeneity in spatial distribution, in which the high supply of WY, SR, and CS showed a decreasing pattern from south to north, mainly in the upper mountainous areas; the high supply of FD was mainly clustered in the central oasis agricultural areas; the specific quantitative values showed that in 2022, the Heihe River Basin was characterized by high supply of WY, SR, and CS , and FD in 2022 were $27.06\times10^8m^3$, 4.79×10^8t, 12.16×10^8t, and 1.93×10^6t, respectively. On the demand side, the pattern of spatial differentiation of ecosystem services contrasts with the pattern of supply, with high demand areas for WY, CS and FD concentrated in the densely populated and economically active oasis townships in the central part of the country, and for SR in the mountainous areas in the south. The total demand for WY, SR, CS, and FD were $50.37\times10^8m^3$, 1.53×10^8t, 0.72×10^8t, and 0.22×10^6t, respectively. Generally speaking, except for the total demand for WY, which is higher than the total supply, the total demand for all other services in the Heihe River Basin is lower than the total supply, and the low supply and low demand areas for all services are distributed in the northern desert area, presenting the unique characteristics of the supply and demand of ecosystem services of the "mountain-oasis-desert" complex system.

The mountain subsystem is an area of high supply of WY, SR and CS, and high demand for SR. The maximum values of the average supply of WY, SR, and CS were in Arou Township, Babao Township, and Nanfeng Township, which are located in the southeastern part of the mountainous subsystem, respectively, and the area with the highest average demand for SR was Zamash Township. This subsystem maintains a high supply of water-producing services due to the topographic rain formed by the high Qilian Mountains, which block water vapor, and is accompanied by alpine snow and ice melt water, which together safeguard river runoff; Its land use type is dominated by woodland and grassland, with high vegetation cover, coupled with the protection of Qilian Mountain National Park, and relatively little interference from human activities, which not only effectively maintains biodiversity, but also enhances the supply capacity of soil conservation and carbon sequestration services through the mechanisms of root sequestration and organic carbon accumulation by the vegetation, respectively. Compared to the oasis and desert subsystems, the mountain subsystem has an advantage in terms of average provisioning, but lags behind in terms of average provisioning of food services due to the small amount of arable land in mountainous areas; its average demand for ecosystem services is moderate, with only the average demand for soil conservation services being significantly higher than that of the other subsystems.

The oasis subsystem is not only an area of high supply of FD, but also an area of high demand for WY, CS and FD. Relying on the fertile arable land resources of the Heihe Alluvial Plain, Minle County, Ganzhou District and Suzhou District form high supply cluster areas for FD, while high-density urban areas, such as Jiayuguan City, Suzhou District and Ganzhou District, become hot spots for WY, CS and high demand for FD. This spatial differentiation stems from the special natural-human coupling mechanism of the midstream oasis, where fertile soil and suitable climate support the intensive agricultural production system; However, the large-scale development of agriculture and the need for adequate water resources into irrigated planting, coupled with the high population pressure as the main population concentration area in the Heihe River Basin, makes the system a major water-carbon-food pressure center in the basin. Compared to the mountain and desert subsystems, this subsystem is in the middle of the average supply of the three services, except for the FD, which leads the average supply; Its average total demand is higher than that of the other subsystems, and of the ecosystem services, only the SR has an average demand in the middle, while the remaining services have the highest average demand.

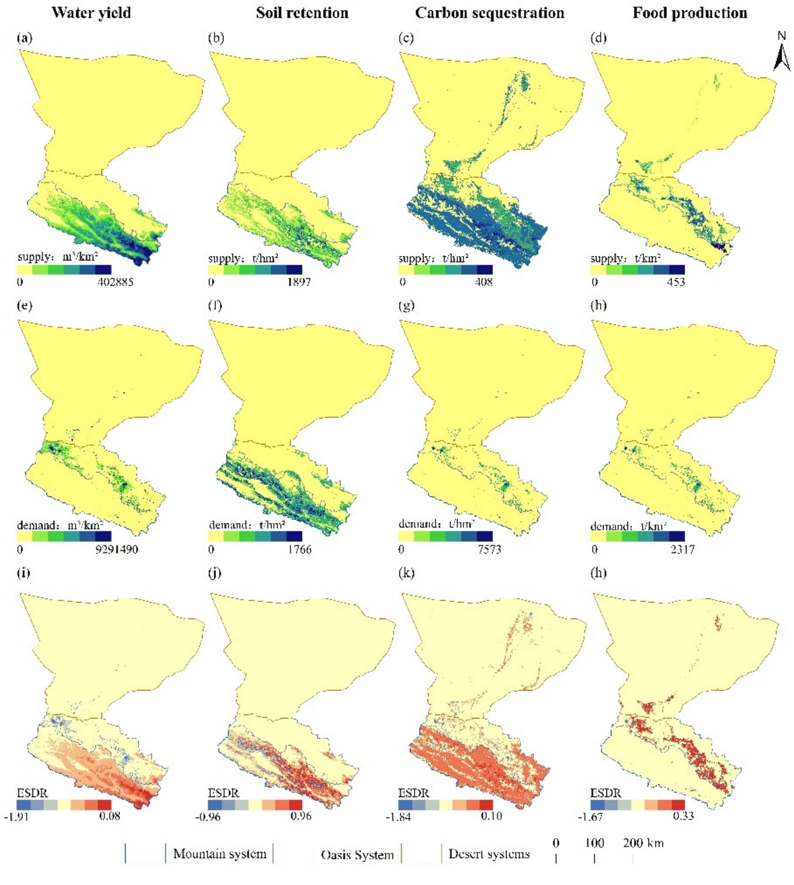

Fig 3. Spatial distribution of ecosystem supply and demand in the Heihe River Basin

Desert subsystems are areas of low supply and low demand for ecosystem services. The average supply of WY and SR was only 0.00325m^3/km^2 and 0.17t/km^2, respectively, and the high value areas of CS and FD supply were mainly distributed in the cultivated land downstream of the Heihe River; Areas of high demand for WY, CS and FD are mainly located in a band along the mainstem of the Heihe River. This characteristic stems from the special water-heat mix of the arid zone, which is characterized by a scarcity of precipitation, strong evaporation, and a desert-gobi surface, resulting in scarce surface runoff; this, together with the fact that the intensity of human activity is much lower than that of the oasis subsystem, determines that the supply of and demand for all services are low.

Table 3. Average supply and demand of ecosystem services of the mountain-oasis-desert system in the Heihe River Basin

		WY(m^3/km^2)	SR(t/km^2)	CS(t/km^2)	FD(t/km^2)
Mountain subsystem	supply	87995.43	15569.89	19493.05	9.71
	demand	27993.19	5084.15	191.68	0.59
Oasis subsystem	supply	7715.84	1430.14	13201.94	64.80
	demand	76548.29	255.72	2755.95	8.43
Desert subsystem	supply	0.00325	0.17	3633.50	2.49
	demand	25533.65	7.69	62.78	0.19
Total	supply	95711.27	17000.20	36328.48	77.00
	demand	130075.12	5347.57	3010.41	9.21

4.2. Matching Supply and Demand of Ecosystem Services in the "Mountain-Oasis-Desert" System

4.2.1. Matching Analysis of the Quantity of Supply and Demand of Ecosystem Services in the "Mountain-Oasis-Desert" System

Based on the calculation results of the spatial quantitative model of supply-demand balance (Fig. 4), combined with the spatial analysis module of ArcGIS 10.4, a spatial distribution map of ecosystem service supply-demand ratio of the Heihe River Basin was generated (Fig. 3.i, j, k, h). The study reveals that the service supply and demand relationship of the "mountain-oasis-desert" ecosystem in the Heihe River Basin is characterized by significant spatial heterogeneity and gradient differentiation.

In terms of the quantitative characteristics of the integrated supply-demand ratio, the integrated supply-demand ratios of ecosystem services in the mountain, oasis and desert subsystems were 0.72, 0.33 and -0.03, respectively, presenting a gradient pattern of "surplus-equilibrium-deficit". Among them, only the desert subsystem has an integrated supply/demand ratio of ecosystem services less than 0, making it a region with a more serious contradiction between supply and demand in the watershed; in contrast, the mountainous system, with its high vegetation cover and complete ecosystem structure, shows a significant surplus with an integrated supply/demand ratio of 0.72; and the oasis subsystem is in a state of tight equilibrium with a composite value of 0.33, reflecting a combination of high-intensity human activities and natural ecosystems. system, reflecting the delicate balance between high-intensity human activities and natural ecosystems.

Within the mountain subsystem, the supply/demand ratios of all ecosystem services were positive, with the following order: CS (0.98) > FD (0.89) > WY (0.52) > SR (0.51). The supply/demand ratio of CS and FD is significantly higher than that of the downstream oasis and desert subsystems, mainly due to the strong carbon sink capacity of this subsystem with high vegetation cover and rich biodiversity, which maintains the supply advantage of CS in the whole region, but the supply/demand ratio of the mountainous valleys, where human activities are concentrated, decreases in localized supply/demand ratios due to the increase in energy consumption; As an upper basin water-holding area, adequate irrigation water and low-density population distribution have resulted in FD supply exceeding demand; Areas with high supply/demand ratios for WY are concentrated in the headwater areas of rivers in the southeastern part of the basin, which benefit from the dual recharge of natural precipitation and snowmelt and very low human water use; Although the overall supply of soil conservation services exceeds the demand, gravity erosion due to steep topography and concentrated rainfall has resulted in a negative supply/demand ratio in some ecologically vulnerable areas.

Within the oasis subsystem, the supply-demand ratios for each ecosystem service were greater than 0, except for WY, which were ranked as follows: FD (0.77) > SR (0.70) > CS (0.65) > WY (-0.82). The severe deficit in the supply/demand ratio for WY is mainly attributed to the sub-system's location in an arid and semi-arid region with low precipitation and high evaporation, and its location in the middle reaches of the Heihe River Basin where upstream water supply has been reduced, coupled with the over-reliance of intensive irrigated agriculture on external sources of water as the main populated and core agricultural area, which has led to an imbalance in supply/demand; It is worth noting that the ratio of supply and demand of SR in this subsystem is significantly higher than that in other subsystems, mainly due to the effective control of wind and water erosion by artificial protection forests and farmland protection systems in irrigated oasis agriculture, while the mountain subsystem, despite its high vegetation cover, has serious wind erosion in the desert subsystem because of the steep slopes of the mountains, the concentration of rainfall, and the severity of natural erosion.

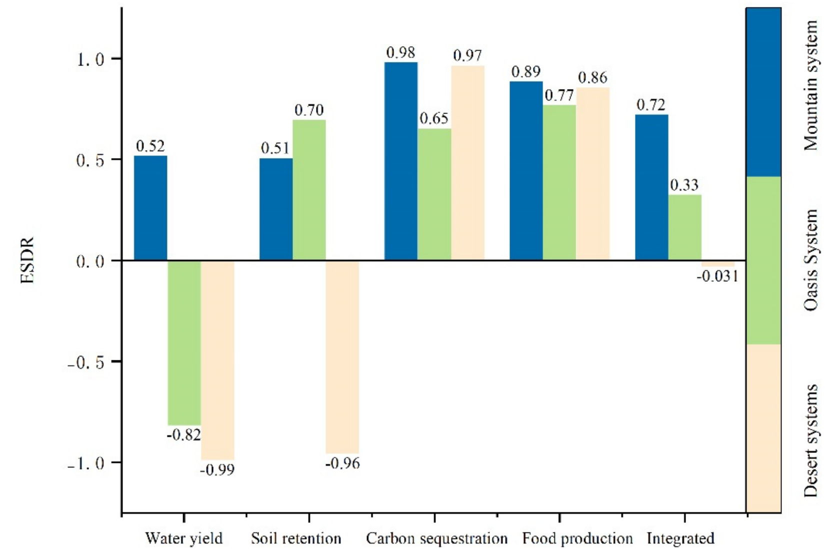

Fig 4. Ratio of ecosystem service supply and demand in the "mountain-oasis-desert" system of the Heihe River Basin

Within the desert subsystem, the ratio of supply and demand for ecosystem services is characterized by extreme polarization; WY (0.99) and SR (-0.96) were in severe deficit, while CS (0.97) and FD (0.86) showed localized surpluses and were both higher than in the oasis subsystem, with the high value areas banded along the mainstem of the Heihe River. The lack of water production capacity in this subsystem due to the extreme arid climate, together with intense wind erosion triggered by sparse vegetation cover, creates a gap in the supply of WY and SR; However, anthropogenic areas along rivers, the introduction of localized artificial oases and drought-tolerant crops create localized CS increments, and low population densities keep food and carbon demand at very low levels, resulting in supply-demand surpluses. It is alarming that the ratio of supply and demand of integrated services of desert subsystems (-0.03) is approaching ecological thresholds and is highly susceptible to a breach of the fragile equilibrium due to the combined effects of climate change and human activities.

4.2.2. Analysis of the Type of Spatial Match Between Supply and Demand of Ecosystem Services in the "Mountain-Oasis-Desert" System

Based on the Z-core standardization method, ArcGIS10.4 was used to construct a mapping of ecosystem service supply-demand matching relationship in the "mountain-oasis-desert" system of the Heihe River Basin (Fig. 5), and an area chart was generated using area tabulation

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to match the area and ratio of supply-demand matching types of ecosystem services for each sub-system (Table 4). The study showed that the matching relationship between supply and demand of ecosystem services in the watershed showed significant spatial differentiation, with the area of the L-L matching type accounting for the largest proportion of each service, and conversely, the spatial extent of the L-H matching type was relatively narrow; The pattern of spatial differentiation is similar to the natural geographic gradient of the "mountain-oasis-desert" system - the mountain subsystem is dominated by the H-L and H-H matching types, and the oasis subsystem is dominated by the L-L and H-L types, The oasis subsystem is characterized by a complex pattern of L-L, H-L, H-H, and a mixture of L-H matches, while the desert subsystem is dominated by L-L match types.

In the mountain subsystem, integrated ecosystem services are dominated by H-H and H-L match types. The eastern and southeastern portions of the WY are recharged by abundant precipitation and snow and ice melt in the Heihe River headwaters flow area, resulting in a H-L match type, while the northwestern portion of the area is dominated by a L-L match type. SR are dominated by a H-H match type, with high intensity natural erosion processes coupled with high soil conservation capacity in steep slope areas, and only in areas with stable natural substrates such as river valleys presenting a L-L match type. CS exhibit a H-L match type due to high vegetation cover and low anthropogenic disturbance. FD are dominated by L-L, mainly due to the high altitude, low temperatures and rugged terrain of mountainous areas, poor conditions for food production and low supply, coupled with low demand for food crops due to low population density.

The oasis subsystem, as the core area of human-land interaction in the watershed, has significant complexity in the type of match between ecosystem service supply and demand. WY is dominated by the L-H matching type, concentrated in Jiayuguan City, Zhangye City center and the surrounding high-density population areas, where the limited water resources and the high-intensity agricultural irrigation and life production demand form a sharp contradiction. SR, due to the degradation of natural vegetation caused by the expansion of construction land and the artificial intervention of the farmland protection forest system, show a L-L match type, although the risk of soil erosion is reduced by engineering measures, the dual decline in the capacity of water retention and the content of soil organic matter leads to a low level of supply-demand equilibrium. CS and FD are mainly of the H-H match type, mainly because of the promotion of water-saving irrigation technology and the optimization of farming conditions in the oasis area, which have enhanced the soil's carbon storage and food supply capacity, in addition to the high demand for CS and FD by the high-density population.

In the desert subsystem, integrated ecosystem services are dominated by the L-L match type, shifting from H-H to H-L match type along the river, with a gradual decrease in water resources in the downstream desert areas and a gradual decrease in the demand for each service from human activities. WY are affected by the extreme arid climate and sparse population distribution, with L-L match types dominating across the region, and localized L-H match types occurring only in irrigated agricultural areas such as Jinta Township due to artificial water demand. SR are dominated by the L-L match type, mainly because desert areas have scarce precipitation and low vegetation cover, and wind erosion leads to soil loss and insufficient supply capacity, while low demand is due to the fact that human activities are low and do not require large quantities of soil to sustain production. The spatial distribution of CS and FD is highly consistent with the combined match type, with the high temperature and arid environment of the vast desert area resulting in very low carbon sequestration capacity of vegetation and crop suitability, and the low population density further reinforcing the pattern of low matching of supply and demand.

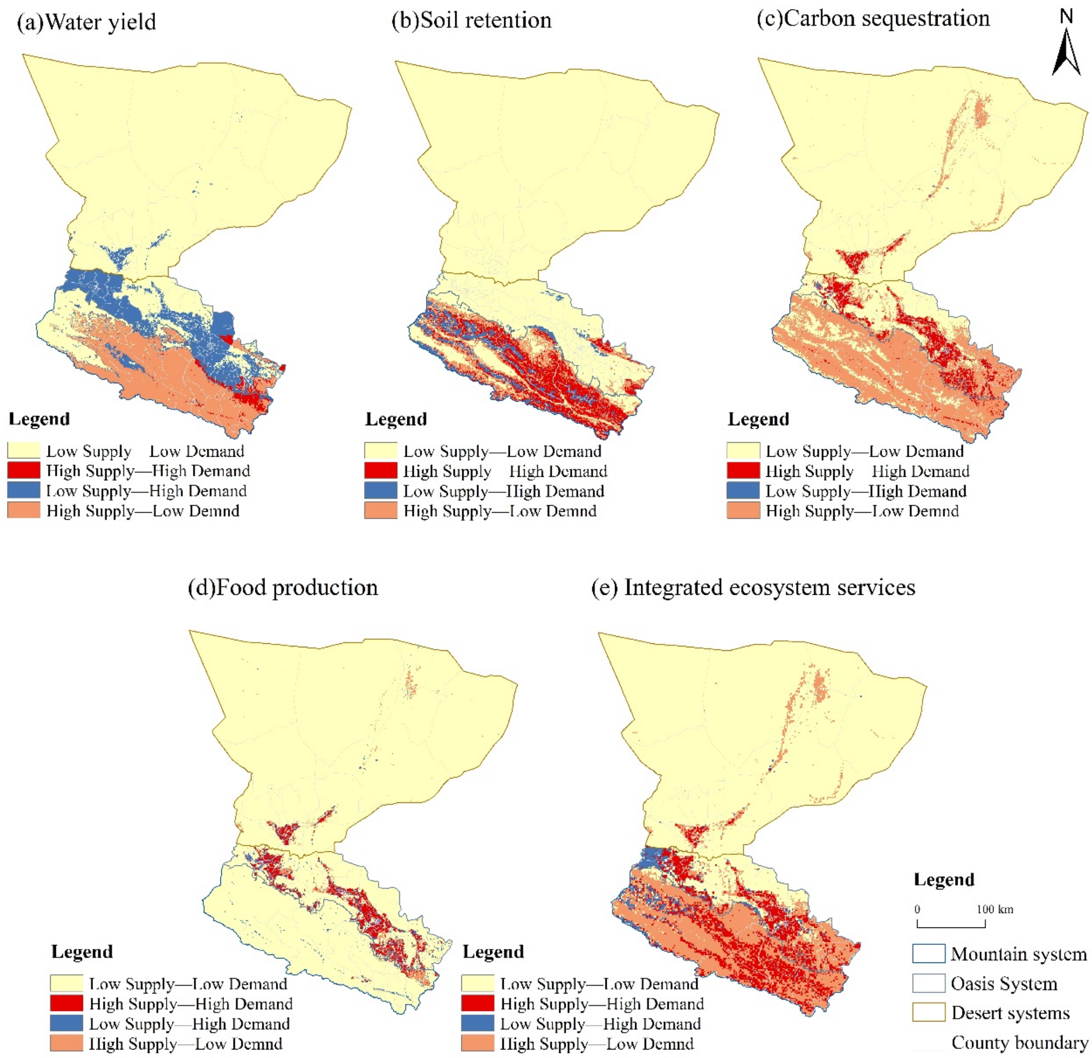

Fig 5. Matching supply and demand of ecosystem services in the "mountain-oasis-desert" system of the Heihe River Basin

Table 4. Area of the Heihe River Basin "mountain-oasis-desert" system of integrated ecosystem service supply-demand match type (km^2)

	H - L	H - H	L - L	L - H
Mountain system	17880.33	8075.57	1101.05	1379.02
Oasis System	5985.38	5613.55	8028.64	1801.39
Desert systems	2707.5	444.03	97303.94	122.74
Total	26573.21	14133.15	106433.63	3303.15
Percentage	17.66%	9.39%	70.75%	2.20%

4.3. Drivers of Ecosystem Service Supply and Demand

The relationship between supply and demand for ecosystem services is essentially the result of the coupling of multiple elements such as the natural environment, socio-economics and landscape patterns. Based on the accessibility and analytical feasibility of natural economic data in the Heihe River Basin, the final driving variables of this study were (1) natural factors: temperature(TEM), precipitation(PRE), evapotranspiration(PET), slope(Slop), slope direction(SD) and normalized vegetation index (NDVI); (2) socio-economic factors: GDP(GDP), population density(POP), nighttime light intensity(NPP); percentage construction land area (Con), percentage of cultivated land area(Cul), and percentage of forested land area(For). Using the factor detector and interaction detector in the Geo Detector, we identified the driving

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mechanism of spatial variation in ecosystem service supply and demand ratios of the "mountain-oasis-desert" composite system in the Heihe River Basin (Fig. 6).

Table 5. Results of detecting the driving factors of ecosystem service supply and demand in the "mountain-oasis-desert" system of the Heihe River basin

	Factor indicators	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12
Mountain system	q Statistics	0.598	0.840	0.475	0.351	0.225	0.463	0.247	0.468	0.312	--	0.446	0.498
	p-value	0.022	0.000	0.110	0.255	0.860	0.096	0.577	0.462	0.892	--	0.361	0.090
Oasis System	q Statistics	0.054	0.104	0.030	0.091	0.025	0.155	0.381	0.502	0.617	0.455	0.093	0.007
	p-value	0.280	0.048	0.577	0.082	0.675	0.007	0.000	0.000	0.000	0.000	0.069	0.960
Desert systems	q Statistics	0.026	0.114	0.128	0.146	0.329	0.131	0.991	0.991	0.983	0.977	0.114	0.003
	p-value	0.968	0.672	0.615	0.547	0.218	0.631	0.000	0.000	0.000	0.000	0.706	0.791

Note: X1: TEM; X2: PRE; X3: PET; X4: Slop; X5:SD; X6: NDVI; X7: GDP; X8: POP; X9: NPP; X10: Con; X11: Cul; X12: For.

The results of the sub-detection showed that the socio-economic factors have dominant explanatory power for the ratio of ecosystem service supply and demand in the Heihe River Basin. Among them, the supply-demand ratio of WY was mainly influenced by POP and NPP, indicating that population agglomeration and urbanization significantly exacerbated water demand pressure. The supply-demand ratio of SR, on the other hand, shows a clear nature-dominated feature, with Slop, PRE and For being the main drivers, indicating that soil erosion is prone to occur in mountainous areas with high slopes and abundant precipitation, highlighting the influence of topography and vegetation cover on the soil conservation function, while socio-economic factors have a relatively weak influence.

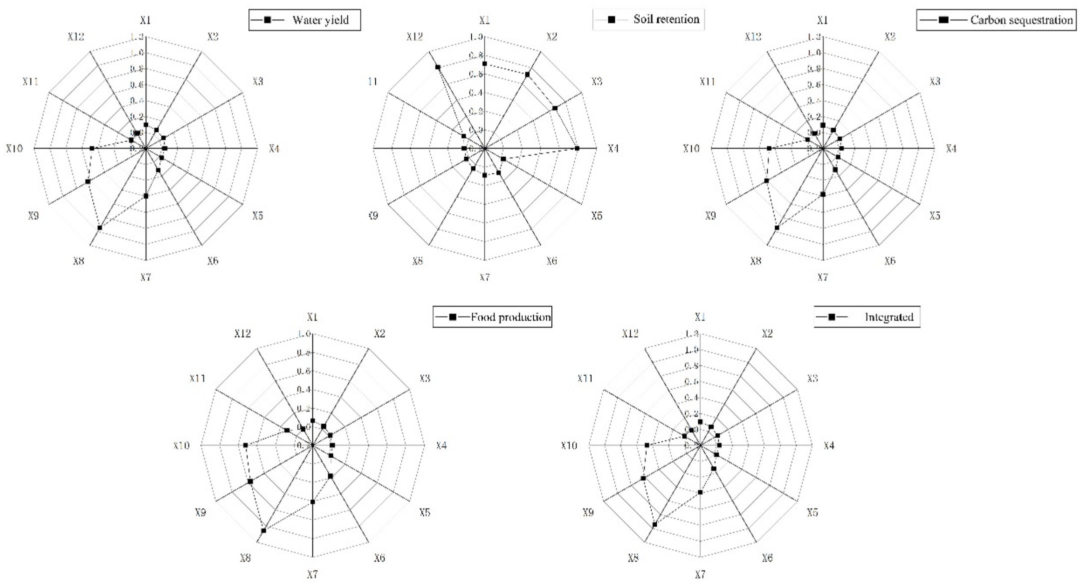

Fig 6. Radar map of Geo Detector detection factor analysis for the Heihe River Basin
Note: X1: TEM; X2: PRE; X3: PET; X4: Slop; X5:SD; X6: NDVI; X7: GDP; X8: POP; X9: NPP; X10: Con; X11: Cul; X12: For.

The ratio of CS to FD supply and demand is mainly driven by POP, NPP and Con, revealing the prominent contradiction between carbon emission and ecological protection needs in anthropogenic intensive areas, as well as the crowding out of arable land resources by the process of urbanization, with Cul's explanatory power q-value of 0.11 contributing to a relatively low level only. The driving pattern of the integrated ecosystem service supply-demand ratio was highly consistent with water production, carbon sequestration and food services, with POP and NPP playing a dominant role as the core drivers influencing the balance between ecosystem service supply and demand in the Heihe River Basin.

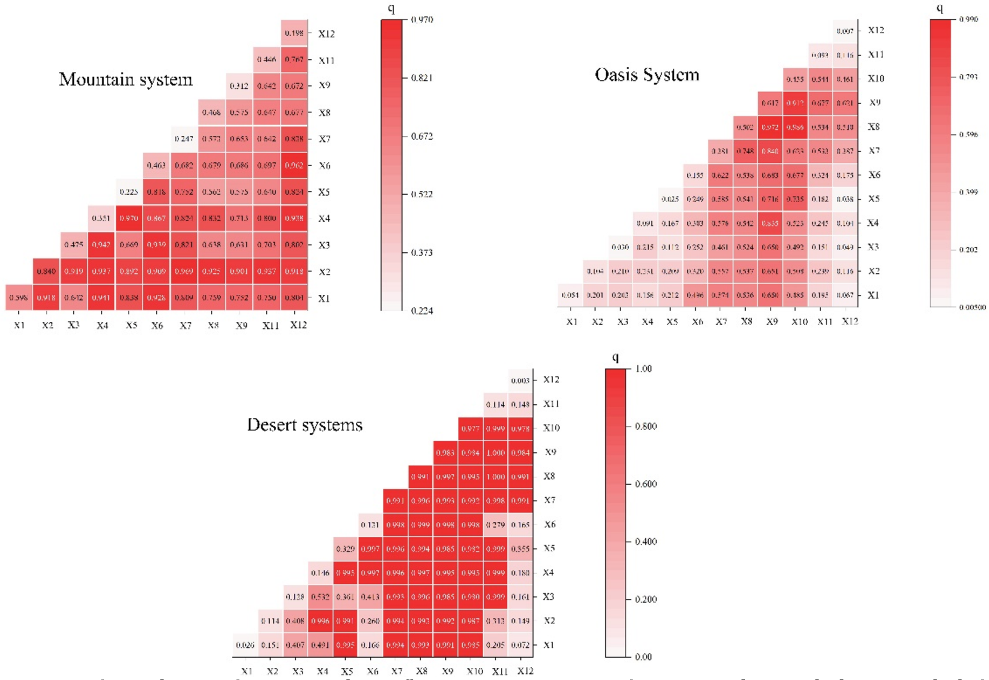

Fig 7. Interaction detection results of ecosystem service supply and demand drivers of mountain, oasis and desert systems in the Heihe River Basin

Note: X1: TEM; X2: PRE; X3: PET; X4: Slop; X5:SD; X6: NDVI; X7: GDP; X8: POP; X9: NPP; X10: Con; X11: Cul; X12: For.

Factor detection and interaction detection of the supply-demand ratio of integrated ecosystem services for each subsystem of mountains, oases, and deserts (Table 5, Fig. 7). The results of the factor probes showed that there were significant differences in the key drivers affecting the ratio of supply and demand of integrated ecosystem services across subsystems. Overall, natural factors are the key drivers influencing the supply and demand of ecosystem services in the mountain subsystem, while socio-economic factors have a stronger explanatory power for the oasis and desert subsystems; In addition, the q-values of GDP, POP, NPP and Con in the desert subsystem are significantly higher than the other subsystems by more than 0.970, highlighting the strong intervention effect of human activities. Specifically, in the mountain subsystem, precipitation with the highest q-value of 0.840 was the dominant driver influencing the supply and demand of ecosystem services in the mountain subsystem, and the rest of the factors in the order of q-statistics were TEM>For>PET>POP>NDVI>Cul>Slope Slop>GDP>SD, with p-values of SD and Cul being insignificant for the mountain subsystem ecosystem services supply and demand weakly. In the oasis subsystem, the p-value is 0 and the q-statistics are ranked as POP > NPP > Con > GDP, indicating that the urbanization process and the intensity of human activities are the key drivers. In the desert subsystem, the p-value is 0 and the q-statistics are ranked as GDP = POPO > NPP > Con. The intervention of human activities in the desert ecology is the key factor influencing the supply and demand of ecosystem services in the desert system, whereas the natural factors have a very low explanatory power due to the high stability of the environment.

Interaction probes further revealed that the interactions between the subsystem factors were nonlinearly enhanced, with the interactions between the factors being greater than those of the individual factors. In the mountain subsystem, interactions among natural factors dominated, with PRE, Slop, and NDVI interacting particularly significantly with other factors, with the interactions of Slop and SD (q=0.970), PRE and GDP (q=0.969), and NDVI and For (q=0.962) having the strongest explanatory power of spatial divergence in ecosystem service supply and demand. In the oasis subsystem, the interactions between socioeconomic factors were more prominent, with significant interactions between GDP, POP, NPP, and Con and other factors, especially the most critical interactions between POP and Con (q=0.986), POP and NPP (q=0.972), and NPP and Con (q=0.912). In the desert subsystem, the interactions within the socioeconomic factors are close to the extremes, while the interactions between the natural and socioeconomic factors are significant; In contrast, the effects of internal interactions within natural factors on the supply and demand of ecosystem services are weak, reflecting the high sensitivity of desert ecosystems to human activities and their low responsiveness to changes in the natural environment; It is worth noting that the interaction between Cul and most of the factors will be close to the extreme value, except for the weak interaction between TEM, PRE and NDVI, which lies in the fact that the expansion of cultivated land area and the increase of built-up land area will exacerbate the depletion of water resources and land sands, which will seriously threaten the stability of the desert ecological environment.

The study reveals that from mountains to deserts, the supply and demand mechanisms of ecosystem services show a significant shift from natural to human-led regulation, and the strength of driver interactions is significantly positively correlated with system vulnerability. The essence of this evolution is that the stability of mountain ecosystems depends on the integrity of natural processes, oasis ecosystems are subject to resource competition and urbanization pressure, and desert ecosystems are at risk of irreversible degradation due to breaches of ecological thresholds.

5. Discussion

Taking the Heihe River Basin as an example, the study on the matching of supply and demand of ecosystem services in the "mountain-oasis-desert" system found that, due to the double influence of natural conditions and socio-economic activities, the subsystems in the "mountain-oasis-desert" complex system in the basin ,The study found that, under the influence of both natural conditions and socio-economic activities, the matching of supply and demand of ecosystem services in each subsystem of the "mountain-oasis-desert" composite system in the watershed differed significantly. The mountain subsystem, driven mainly by natural factors, is the core supply area for WY, SR and CS; the oasis subsystem, as the main concentration of population and economic activities in the watershed, is an area of high demand for ecosystem services; and the desert subsystem, which is ecologically fragile, is in a critical state of imbalance between the supply of and demand for ecosystem services in the face of anthropogenic interventions. The study reveals the complex interaction mechanism between natural endowment and human activities. In the management of the "mountain-oasis-desert" composite system, it is not only necessary to formulate appropriate management policies for each sub-system according to the specific natural environment and socio-economic development of the local area, but it is also necessary to pay more attention to the totality of the watershed and the mobility of the material between the systems, so that each sub-system will not be included in the management of the "mountain-oasis-desert" composite system. The management of subsystems should not be isolated from other systems. Based on this, the ecological management of the Heihe River Basin should follow the synergistic development strategy of "keeping water in the south, locking sands in the north and revitalizing the oasis in the middle".

Integrity protection as a core objective in the management of mountain subsystems. As a key area for water conservation in the basin, once the mountain ecosystem is damaged, its natural recovery cycle is long, and it directly affects the water supply of the oasis and desert subsystems in the middle and lower reaches of the basin. Therefore, the management strategy should be based on the principle of natural restoration, through reducing human interference, strengthening water conservation and biodiversity protection, and continuing to promote the return of farmland to forests and grasslands, mountain forestation and ecological migration projects, so as to improve the coverage of forest and grassland vegetation, and thus enhance the supply capacity of WY, SR and CS. At the same time, the core area of Qilian Mountain National Park, key forest areas for water conservation and biodiversity hotspots are included in the red line of ecological protection, and industrial and mining development, reclamation of steep slopes and construction of large-scale tourism facilities are strictly limited, so as to build a solid ecological security barrier at the upper reaches of the basin.

The main focus in the management of the Oasis subsystem is to regulate development. The oasis subsystem plays a pivotal and driving role in the mountain and desert subsystems, and is also an important commodity grain base in China. It should focus on developing water-saving, efficient, intensive and sustainable industries to alleviate the pressure on the mountains and deserts in the south and north, and to support the protection and environmental construction in the north and south. Strengthen the optimal management of water resources, develop high-standard water-saving farmland, upgrade water-saving irrigation technology to conserve efficient water use; solve the contradiction between production, living and ecological water use, maximize water storage through vegetation water conservation, soil water storage, water collection in reservoirs, reduce the loss of water in the process of water transmission through canals or pipelines, and improve the efficiency of water transmission, so as to solve the problem of imbalance between the supply of and demand for WY. At the same time, it has implemented an appropriate deconcentrating strategy for highly populated areas to ease the pressure of human activities on the ecological environment; it has also strengthened the construction of peripheral protective forest systems and farmland ecosystems in the oasis to enhance the stability of SR and CS and to form a spatial pattern for the coordinated development of "production-life-ecology".

Restoration governance as a key orientation in the management of desert subsystems. Under the great threat of extreme drought and desertification, the desert subsystem has a serious shortage of WY and SR supply capacity, and the ecosystem is in a fragile and critical state, so the focus is on vegetation restoration and the strengthening of ecological construction. Governance needs to focus on vegetation restoration and wind-sand prevention and control, control unreasonable land development activities through measures such as returning farmland to grassland, rotating grassland fallow grazing, and planting drought-resistant crops, maximize the restoration of surface vegetation, enhance the soil's resistance to erosion, and improve the soil's ability to retain water. The process of desertification is being controlled through ecological restoration projects such as windbreaks and sand fixation, sand dune fixation, farmland protection forests and water-irrigation and sand-blocking forests. With regard to the use of water resources, it has promoted water-collection projects and high-efficiency water-saving irrigation techniques, optimized the allocation of water resources in the oasis areas along the rivers, and strictly controlled irrational land development activities, so as to avoid further aggravation of the contradiction between the supply of and demand for ecosystem services.

6. Conclusion

This paper takes the Heihe River Basin as an example, assesses the supply and demand of the four ecosystem services of WY, SR, CS and FD in the "mountain-oasis-desert" system and analyzes the characteristics of spatial changes from the perspective of supply and demand, to explore the matching of supply and demand of ecosystem services, and on the basis of this, explores the factors affecting the ratio of ecosystem services supply to demand. On the basis of this study, the driving factors affecting the ratio of ecosystem service supply and demand will be explored, and the actual state of ecosystem services in the Heihe River Basin will be identified, so that the ecological environment of the "mountain-oasis-desert" system can be better understood and managed, and the sustainable development of the basin can be realized.

(1) The supply and demand of ecosystem services in the Heihe River Basin show obvious gradient differentiation and spatial heterogeneity. Overall, the total supply of services is greater than the total demand for the remaining three services, except for WY, where the total supply of services is less than the total demand; The mountain subsystem is an area of high supply of WY, SR and CS and high demand for SR; the oasis subsystem is an area of high supply of the main FD and high demand for WY, CS and fFD; and the desert subsystem is an area of low supply of and demand for all ecosystem services, with limited carbon sequestration and food production only in localized, man-made oases along the rivers.

(2) The supply and demand of ecosystem services of the Heihe River shows a spatial gradient pattern of "mountain surplus - oasis balance - desert deficit". Among them, the supply of ecosystem services of each subsystem is relatively adequate, and only the integrated supply/demand ratio of ecosystem services of the desert subsystem is less than 0, which is the area with more serious contradiction between supply and demand in the basin; In terms of match types, the mountain subsystem is dominated by H-L and H-H match types, the oasis subsystem is dominated by L-L, H-L, H-H, and mixed L-H match types; and the desert subsystem is dominated by L-L match types.

(3) The main driving factors affecting the ratio of supply and demand of ecosystem services in the Heihe River Basin at the basin-wide scale are socio-economic factors, with the ratio of supply and demand of SR dominated by natural factors. Factor detection showed that there were significant differences in the key drivers affecting the supply-demand ratio of integrated ecosystem services in the subsystems, with the mountain subsystem dominated by natural factors, and PRE, TEM, and For being the main drivers; Socio-economic factors are the main drivers influencing the ratio of ecosystem service supply and demand in oasis and desert subsystems. The mountain subsystem is centered on interactions among natural factors, and the interactions of PRE, Slop, and NDVI with other factors are significantly stronger than the interactions among other factors; the oasis subsystem has significant interactions among socioeconomic factors, and the interactions of GDP, POP, NPP, and Con with other factors are significantly stronger than the interactions among other factors; and the desert subsystem has a social in the desert subsystem, the interaction within the socio-economic factors is close to the extreme value, except that the interaction between the natural factors and the socio-economic factors is also significant.

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