

Article

Supply and Demand Balance of Ecosystem Services in the Ulanbuh Desert

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Abstract

Desert ecosystems play a critical role in global climate regulation. Current research reveals a relative lack of research regarding desert ecosystem service (ES) supply and demand. Therefore, we selected the Ulanbuh desert, one of the eight major deserts in China, as study area. Using specialized models, we quantify the supply and demand of four ES, including water yield (Wy), soil conservation (Sc), windbreak and sand fixation (Ws), and carbon sequestration (Cs), from 1985 to 2020. Univariate linear regression analysis and panel data analysis (PDA) were used to examine trends in desert ES supply–demand ratio (ESDR) and its determinants. The findings indicated that ES supply presented increases in Sc and Cs, and decline in Ws from 1985 to 2020. Demand patterns showed a growth trend for Wy and Cs. ESDR revealed that Sc, Ws, and Cs show an excess of supply over demand and are in a decreasing trend, while Wy displays a supply deficit relative to demand with no significant change. The comprehensive ESDR decreased over the study period, with a supply-deficit status emerging in the southwestern area. Natural factors (NDVI and precipitation) and socio-economic factors (GDP and population density) served as the main factors affecting the comprehensive ESDR. This research provides a novel perspective for desert ecosystems management and conservation, emphasizing the necessity of incorporating the ES supply and demand balance into regional development policies to achieve sustainable development in arid regions.

Keywords: desert ecosystem; ecosystem services; temporal dynamics; supply and demand; driving factors



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1. Introduction

Serving as a vital mediator between environment and human welfare [1,2], ecosystem services (ES) are indispensable for sustainable management in preserving global ecological stability and anthropogenic advancement. A comprehensive understanding of ES necessitates systematic evaluation of both supply and demand [3,4]. ES supply denotes ecological processes generating tangible benefits for human livelihoods, while the desired level of service that humans aspire to achieve defines ES demand [5,6]. At present, the

dual pressures of global climate change and anthropogenic interventions have significantly impacted the ES supply and demand [7]. Environmental stressors and human activities degrade ecosystem structures, altering the capacity to deliver products and services [8,9]. Meanwhile, population growth and economic activities amplify societal ES demand [10].

The ES supply and demand serve as critical indicators for assessing the transfer from nature to human society, offering insights into the potential for sustainable nature–human symbiosis [11,12]. However, when demand exceeds supply, it can lead to the degradation of ES quality and increased regional risk [13]. Recently, investigating the ES supply and demand has emerged as a focal area in the field of sustainable ecology [14]. Scholars have introduced the concept of the ecosystem services supply–demand ratio (ESDR) to capture the spatial variability in supply and demand scenarios, which provides a nuanced view for spatial mismatch analysis [15–18]. Current research endeavors on ESDR have largely centered on quantifying balance under static conditions and mapping spatial distributions [16,19]. Different scholars have utilized ESDR to investigate the spatial distribution of supply and demand across diverse regions, including metropolitan clusters (Beijing–Tianjin–Hebei area), provincial territories (Shandong Province), and arid zones (the Bairin Left Banner) [20–22]. This research indicates spatial heterogeneity in the mismatch of ES supply and demand, with climate and socio-economic elements being pinpointed as crucial causes [23–25].

The desert ecosystem constitutes a vital component of terrestrial ecosystems [26], providing essential ES, such as windbreak and soil fixation (Ws) and carbon sequestration (Cs), to the maintenance of global ecological balance and climate conditions [27]. Deserts support unique biodiversity [28], including specialized terrestrial vertebrate species and endemic biota adapted to extreme environmental conditions [29]. Meanwhile, approximately 6% of the global population relies on desert-specific resources to meet cultural and subsistence needs [30]. Notably, the slow recovery rates of desert ecosystems amplify uncertainties regarding vegetation degradation and the deficit in ES supply and demand caused by desertification [31,32]. Although many initiatives have been made globally for desertification control, existing studies still mainly focus on high productivity regions, such as forests and grasslands [33–35], and the quantification of ES in desert ecosystems remains critically understudied. Therefore, analyzing the ESDR and its determinations in desert ecosystems is not only critical to optimizing desert land use and resource management, but also the theoretical basis for improving policies for global desertification control.

The Ulanbuh Desert is one of the eight major deserts in China and is located in the core area of the northern windbreak and sand fixation belt [36]. It is a key node for the ecological barrier of northwest China and the ecological security of the Yellow River Basin, and the study of its ES supply and demand has irreplaceable strategic value. It plays a significant role in consolidating the Northern Ecological Security Barrier. Based on the above research context, this study selected Ulanbuh Desert as an example, aiming to achieve the following: (1) Quantify the spatial and temporal dynamics of supply and demand for four ES, Wy, Sc, Ws and Cs, and ESDR for the period 1985–2020. (2) Identify the main determinants affecting the $ESDR_C$. The findings establish an empirical foundation for desert ecosystem management and sustainable regional transitions, offering critical insights to strengthen the Northern Sand Prevention Belt and enhance ecological security in North China.

2. Materials and Methods

2.1. Study Area

The Ulanbuh Desert is located in the northwest region of Inner Mongolia Autonomous Region in northern China, extending across the Alshan League and Bayan Nur of Inner Mongolia (39°17′–40°46′ N, 105°24′–107°01′ E), with an area of about 1.3×10^6 hm²

(Figure 1). The terrain of the area is marked by a low middle and high surroundings, with elevations ranging from 980–1499 m. The region is predominantly defined by a temperate arid climate with low precipitation (110–160 mm) and high evapotranspiration (2380 mm). The Yellow River serves as the principal water source for the region. And its mean annual temperature is 8.6 °C with a large diurnal temperature difference [37]. The natural vegetation is dominated by hyper-arid and arid types of desert vegetation and halophytic vegetation [38].

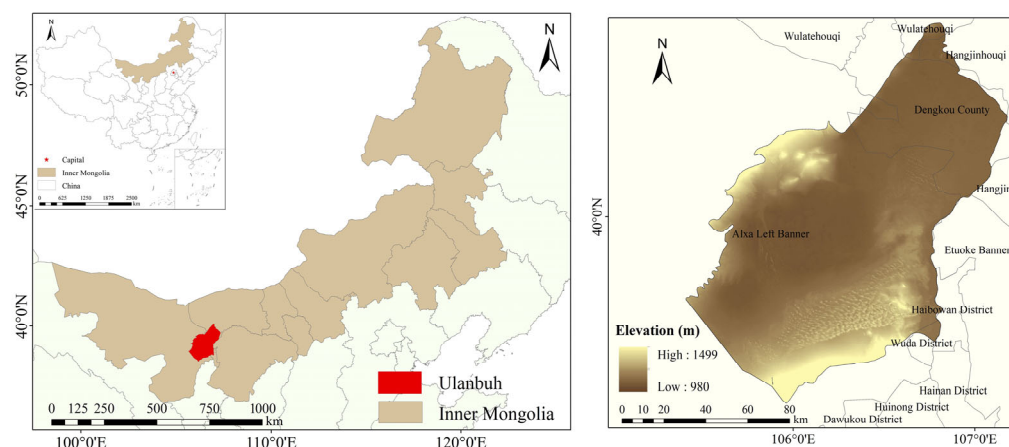


Figure 1. Location and topographic subregions of Ulanbuh Desert.

2.2. Data Sources

The natural and socio-economic data collected specifically include eight periods of time: 1985, 1990, 1995, 2000, 2005, 2010, 2015, and 2020, with a uniform spatial resolution of 1 km. Meteorological data from the region and its neighboring meteorological stations were obtained by Kriging interpolation to obtain meteorological raster data. The water consumption data in the Inner Mongolia Water Resources Bulletin includes water used for livestock and fishery, forestry, irrigation, industry, urban and rural life, and ecological environment, and the relevant missing data were found by reviewing literature. Potential evapotranspiration (PET) in the study area was calculated using the Modified-Hargreaves method [39]. The standardized precipitation evapotranspiration index (SPEI) was calculated by using python's gma library. The NDVI data were obtained using Landsat 5/7/8, using the GEE platform, after de-clouding and filtered processing. The data sources used in this study are listed in Table 1.

Table 1. The data sources of this study.

Data Type	Variable	Unit	Resources
Meteorological	Solar radiation (SR)	%	National Meteorological Information Center (http://data.cma.cn/)
	Mean annual temperature (MAT)	°C	
	Mean annual precipitation (AP)	mm	
	Wind speed	m/s	
Physical geography	Land-use type	-	Data Sharing and Service Portal (https://data.casearth.cn/)
	Soil database	%	National Tibetan Plateau Scientific Data Center (http://data.tpdc.ac.cn/)
	Normalized difference vegetation index (NDVI)	-	Google Earth Engine (https://earthengine.google.com/)

Table 1. Cont.

Data Type	Variable	Unit	Resources
Socio-economic factors	Digital elevation model (DEM)	m	Geospatial Data Cloud (http://www.gscloud.cn/)
	Carbon emissions data	t·people ^{−1}	Carbon Emission Accounts and Datasets (CEADs) (https://www.ceads.net.cn/)
	Water consumption data (water for irrigation of farmland, forestry, animal husbandry, fishery and livestock, industry, urban and rural life, and the ecological environment)	m ³ ·people ^{−1}	Water Resources Department of Inner Mongolia Autonomous Region (https://slt.nmg.gov.cn/)
	Population density (PD)	people·km ^{−2}	Resources and Environmental Science and Data Center, Chinese Academy of Sciences (https://www.resdc.cn/)
	Gross domestic product (GDP)	million yuan·km ^{−2}	

2.3. ES Supply

2.3.1. Water Yield (Wy) Supply

The Wy is the capability of ecosystems to capture and store water from rainfall or surface runoff through natural processes [36]. The Wy supply of Ulanbuh Desert in this study was quantified by the “water yield” of the InVEST 3.14 model.

2.3.2. Soil Conservation (Sc) Supply

The mitigation of soil erosion by leveraging the structures and processes of ecosystem is regarded as Sc [40]. The Sc supply was assessed by the revised universal soil loss equation (RUSLE) model [41].

2.3.3. Windbreak and Soil Fixation (Ws) Supply

The Ws denotes the function as wind speed reduction and sand and storm suppression [42]. In terms of the difference between the potential soil wind erosion under vegetation cover and the actual soil wind erosion under bare soil conditions [43], the revised wind erosion equation (RWEQ) model can quantify the Ws supply [44].

2.3.4. Carbon Sequestration (Cs) Supply

The Cs is the process by which vegetation converts atmospheric CO₂ into organic matter through photosynthesis and then fixes it into the soil [45,46]. This study quantified the net primary productivity of Ulanbuh Desert by the net primary productivity (NPP) calculation model which was developed by Zhu based on the Carnegie–Ames–Stanford approach (CASA) model [47], and then the Cs was calculated by the carbon conversion factor [46,48].

2.4. ES Demand

2.4.1. Wy Demand

This study adopted actual human water consumption as an indicator to represent the demand for Wy. Given the difficulty in obtaining water usage data from the counties and banners within the Ulanbuh Desert, this study selects the per-capita water consumption calculated based on the water usage and population data from the Water Resources Bulletin of the Inner Mongolia Autonomous Region [49]. Finally, the product of per-capita water used and population density is used as the demand for Wy.

2.4.2. Sc Demand

The severity of soil erosion is directly proportional to the demand for soil management which humans expect [50]. The demand for Sc represents the societal need to mitigate the negative impacts of soil erosion. We operationalize this demand as the potential soil loss that society aims to prevent. Consequently, the actual amount of soil erosion was adopted as the Sc demand [51].

2.4.3. Ws Demand

Analogous to Sc demand, the demand for Ws signifies the societal need to reduce the detrimental effects of wind-driven soil loss. The actual wind erosion was considered as a problem that people hope to solve, leading us to hypothesize that it corresponds to the demand for Ws [52]. Therefore, the actual soil wind erosion was regarded as Ws demand.

2.4.4. Cs Demand

The demand for Cs is characterized as the anthropogenic pressure on ecosystems to offset carbon dioxide emissions. Therefore, the Cs demand is characterized based on per-capita carbon emissions in this study [53]. Considering the availability of data, this study obtained carbon emission data for China from 1985 to 2020 by consulting the China Emission Accounts and Datasets (CEADs), and used population data to calculate the per-capita carbon emissions [54]. Finally, the product of per-capita carbon emissions and raster data on population density is used to find the demand for Cs.

2.5. Supply and Demand for ES and Driving Factors

2.5.1. Supply and Demand

This ESDR introduced to characterize the balance state between the ES supply and demand in this study [55]. The detailed formula is presented below:

$$ESDR = \frac{S - D}{\frac{(S_{max} + D_{max})}{2}}, \quad (1)$$

where S represents the actual amount of ES supply, while D signifies the ES demand. S_{max} denotes the maximum values of ES supply, and D_{max} denotes the maximum values of ES demand. When $ESDR > 0$, it denotes a surplus condition where the service supply outstrips demand. When $ESDR = 0$ it signifies equilibrium between supply and demand. Conversely, when $ESDR < 0$, it implies a deficit scenario where supply falls short of demand.

The $ESDR_C$ was employed to characterize the ES supply and demand in the research area. The formula is outlined below:

$$ESDR_C = \frac{1}{n} \sum_{i=1}^n ESDR_i, \quad (2)$$

where n implies the number of types of ES ($n = 4$, including Wy, Sc, Ws, and Cs, in this study). $ESDR_i$ signifies the supply–demand ratio of the i th ES, which include Wy supply and demand ratio ($ESDR_{Wy}$), Sc supply and demand ratio ($ESDR_{Sc}$), Ws supply and demand ratio ($ESDR_{Ws}$), and Cs supply and demand ratio ($ESDR_{Cs}$).

2.5.2. Analysis of Driving Factors

Panel data analysis (PDA) is a commonly used regression analysis method in econometrics that considers both time and cross-sectional dimensions simultaneously. In this study, different points represented different cross-sections, while different years reflect the time series nature of the data. To enhance the precision of our findings, we chose annual data spanning from 1985 to 2020 for the driving factors analysis. Considering the actual

situation and data availability, we selected twelve indicators as drivers from the three dimensions of nature, land use, and socio-economics by combining the existing relevant studies [38,56,57] on arid zones and the unique geographic characteristics of the Ulanbuh Desert (Table 2). With the aid of Stata 18 software, a panel data model was constructed using the selected driving factors as independents and $ESDR_C$ as the dependent. Common models include mixed-, random-, and fixed-effects models [58].

Table 2. The driving factors to effect on supply-demand ratio.

Types	Driving Factors	Units
Natural Factors	AP	mm
	MAT	°C
	PET	mm
	SR	%
	SPEI	-
	NDVI	-
Land Use Factors	Dunes Proportion (DP)	%
	Cultivated Proportion (CP)	%
	Construction Proportion (CsP)	%
Socio-Economic Factors	Policy Implementation (PI)	-
	PD	people·km ⁻²
	GDP	million yuan·km ⁻²

Considering the potential interactions among the independent variables, performing a multicollinearity test on the independent variable data is crucial. The variance inflation factor (VIF) served as a standard measure to assess multicollinearity within the dataset, where a VIF score exceeding 10 suggests the existence of multicollinearity [59]. Upon examination, the VIF of all factors were found to be less than 10. Therefore, this study sequentially utilized both the fixed- and random-effects models for regression analysis (Tables 3 and 4). Following this, the Hausman test was administered to ascertain the appropriate model. Consequently, adopting the fixed effects model is deemed more appropriate [58].

Table 3. Results of random-effects model.

X_i	Coef.	Std.err	t	$P > t $
AP	−0.0321	0.0017	−18.41	0.000
MAT	−0.2250	0.0027	−84.82	0.000
PET	0.0001	0.0013	0.10	0.919
SR	0.0019	0.0026	0.72	0.469
SPEI	−0.0415	0.0176	−2.36	0.018
NDVI	−0.6823	0.0333	−20.48	0.000
DP	0.0052	0.0014	3.59	0.000
CP	−0.0349	0.0013	−27.01	0.000
CsP	0.0038	0.0008	4.72	0.000
PI	0.4635	0.0087	53.46	0.000
PD	−0.0597	0.0023	−25.70	0.000
GDP	−0.0055	0.0013	−4.32	0.000
$Prob > F = 0.0000$				
$R^2 = 0.2634$				

2.6. The Univariate Linear Regression Trend Test

To explore multiyear trends in supply, demand, and ESDR dynamics across the Ulanbuh Desert from 1985–2020, a univariate linear regression analysis was employed. This study determined the significance level of the trend test by comparing the p -value with

0.05, and the annual rate of change by the slope of the univariate linear regression equation. The results were categorized into five categories based on the magnitude of the *slope* and *p*-value: insignificant increase (*slope* > 0 and *p* ≥ 0.05), significant increase (*slope* > 0 and *p* < 0.05), insignificant change (*slope* = 0), insignificant decrease (*slope* < 0 and *p* ≥ 0.05), and significant decrease (*slope* < 0 and *p* < 0.05). The specific calculation formula for the slope is

$$\text{slope} = \frac{n \times \sum_{i=1}^n i \times Y_i - \sum_{i=1}^n i \sum_{i=1}^n Y_i}{n \times \sum_{i=1}^n i^2 - (\sum_{i=1}^n i)^2}, \quad (3)$$

where slope represents the coefficient of the regression equation. *n* is the number of years (*n* = 8, in this study). *Y_i* refers to the supply/demand value in the *i*th year.

Table 4. Results of fixed-effects model.

<i>X_i</i>	<i>Coef.</i>	<i>Std.err</i>	<i>t</i>	<i>P</i> > <i>t</i>
AP	−0.1612	0.0058	−27.78	0.000
MAT	0.0090	0.0062	1.45	0.147
PET	0.0123	0.0016	7.75	0.000
SR	−0.0516	0.0095	−5.41	0.000
SPEI	−0.3253	0.0226	−14.38	0.000
NDVI	−1.0294	0.0425	−24.24	0.000
DP	−0.0058	0.0019	−2.99	0.003
CP	−0.0611	0.0014	−44.24	0.000
CsP	−0.0266	0.0010	−25.69	0.000
PI	0.3377	0.0117	28.98	0.000
PD	−0.1438	0.0055	−26.06	0.000
GDP	−0.0146	0.0016	−9.34	0.000
<i>Prob</i> > <i>F</i> = 0.0000				
<i>R</i> ² = 0.1022				

3. Results

3.1. Changes in ES Supply

From 1985 to 2020, there were obvious spatial distributional differences in Wy supply variability within the study area (Figure 2). Specifically, the central region exhibited mainly insignificantly changed in Wy supply, the northeastern part was insignificantly decreased, and the eastern and western parts were insignificantly increased. There were not distinct spatial differences in the overall changes in Sc, Ws, and Cs supply. The Sc and Cs exhibited an overall insignificant increasing trend, and Ws showed an overall insignificant decrease.

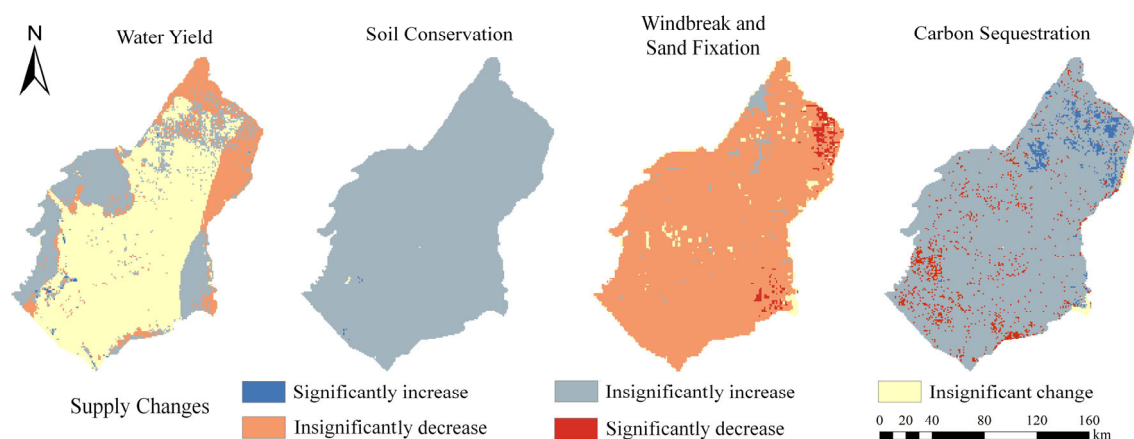


Figure 2. Trend of supply of Wy, Sc, Ws, and Cs in the Ulanbuh Desert from 1985 to 2020.

3.2. Changes in ES Demand

From 1985 to 2020, there have been notable spatial distribution differences in the changes in demand for both Sc and Ws , whereas the changes in demand for Wy and Cs have exhibited no significant spatial distribution variations (Figure 3). Specifically, Sc and Ws demonstrated a decreasing trend in the northeastern part of the study area, accompanied by an increasing trend in the central and southwestern areas. Both Wy and Cs showed an overall upward trend.

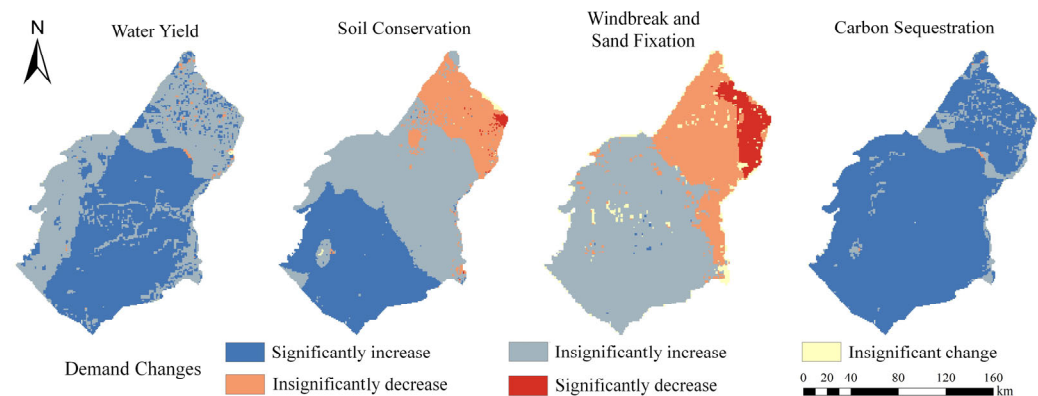


Figure 3. Trend of demand of Wy , Sc , Ws , and Cs in the Ulanbuh Desert from 1985 to 2020.

3.3. Changes in Supply-Demand Ratio for ES

All ESDR exhibited similar spatial distributions, consistently demonstrating a spatial mismatch between supply and demand from 1985 to 2020 (Figure A1). Therefore, only the spatial distribution for 2020 is presented (Figure 4). Overall, $ESDR_{Sc}$, $ESDR_{Ws}$, $ESDR_{Cs}$, and $ESDR_C$ displayed a surplus status. However, it observed localized deficits in the southwestern region for $ESDR_{Sc}$, $ESDR_{Ws}$, and $ESDR_C$, as well as in the northeastern region for $ESDR_{Cs}$. $ESDR_{Wy}$ exhibited an overall deficit status, while a notable surplus was identified in the eastern Yellow River coastal area.

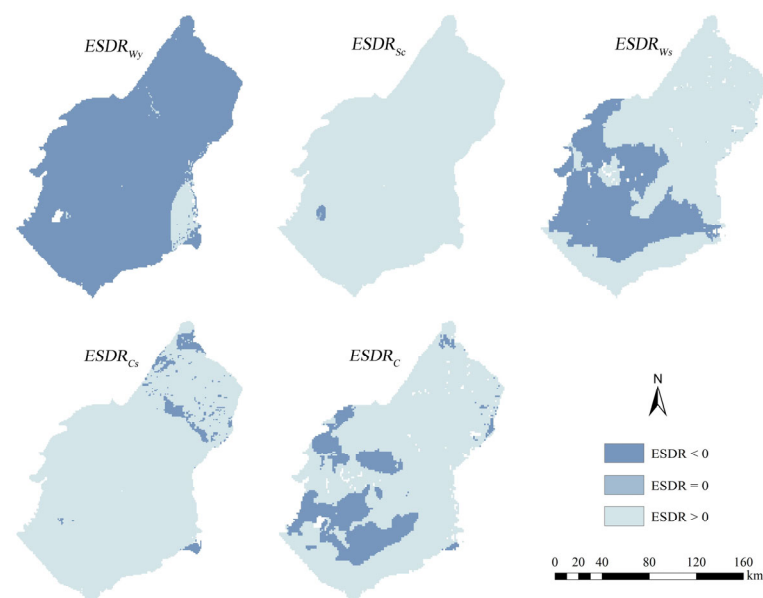


Figure 4. The spatial distribution $ESDR_{Wy}$, $ESDR_{Sc}$, $ESDR_{Ws}$, $ESDR_{Cs}$, and $ESDR_C$ in the Ulanbuh Desert in 2020.

The overall trend from 1985 to 2020 showed an insignificant change in $ESDR_{Wy}$ and decreasing trends in $ESDR_{Sc}$, $ESDR_{Ws}$, $ESDR_{Cs}$, and $ESDR_C$. However, there was spatial

differentiation in the supply–demand ratio for each service. Specifically, there was an insignificant upward trend of $ESDR_C$ in the northeastern region, while the remaining regions showed an insignificant downward trend (Figure 5). The $ESDR_{Ws}$ followed the same trend as $ESDR_C$. However, the $ESDR_{Wy}$ showed insignificant change in its spatial distribution, the $ESDR_{Cs}$ demonstrated an insignificant downward trend. The $ESDR_{Sc}$ increases slightly in the northeastern and southern regions, and decreases slightly in other areas.

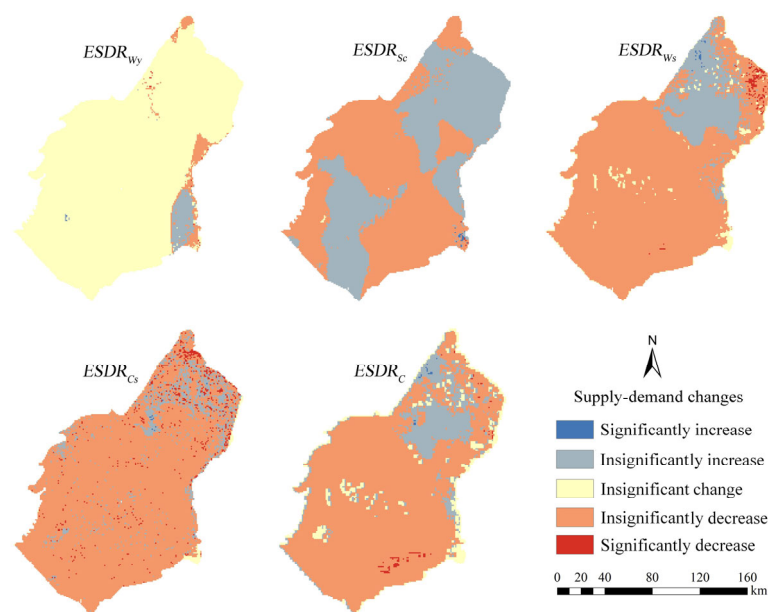


Figure 5. Trend of supply–demand of $ESDR_{Wy}$, $ESDR_{Sc}$, $ESDR_{Ws}$, $ESDR_{Cs}$, and $ESDR_C$ in the Ulanbuh Desert from 1985 to 2020.

3.4. Driving Factors

The random-effects model results indicate that PET and SR were not statistically significant (Table 3). In the fixed-effects model, MAT failed to achieve statistical significance (Table 4). The Hausman test, where the null hypothesis posits that the random effects model is appropriate, yielded a result of $Prob > \chi^2 = 0.0000$, which is significantly less than 0.05 (Table 5). Consequently, we reject the null hypothesis, indicating that the fixed-effects model is more appropriate. At the same time, the size of the final impact factor is determined based on the test results of the fixed-effects model.

Table 5. Results of Hausman test.

	<i>fe</i>	<i>re</i>	<i>Difference</i>	<i>S.E.</i>
AP	−0.1612	−0.0321	−0.1291	0.0055
MAT	0.0090	−0.2250	0.2340	0.0056
PET	0.0123	0.0001	0.0122	0.0009
SR	−0.0516	0.0019	−0.0535	0.0092
SPEI	−0.3253	−0.0415	−0.2838	0.0142
NDVI	−1.0294	−0.6823	−0.3471	0.0263
DP	−0.0058	0.0052	−0.0110	0.0013
CP	−0.0611	−0.0349	−0.0262	0.0005
CsP	−0.0266	0.0038	−0.0304	0.0007
PI	0.3377	0.4635	−0.1258	0.0078
PD	−0.1438	−0.0597	−0.0841	0.0050
GDP	−0.0146	−0.0055	−0.0091	0.0009

$Prob > \chi^2 = 0.0000$

Note: *fe* represents the regression coefficients for the fixed-effects model, while *re* refers to the regression coefficients for the random-effects model. *Difference* denotes the discrepancy between *fe* and *re*. *S.E.* stands for standard error.

In the analysis of driving factors of $ESDR_C$, MAT was not tested for significance. Among the factors that passed the significance test, NDVI, AP, and SPEI are the main natural factors (Figure 6a), and GDP and PD are the primary socio-economic factors (Figure 6b). Regrading land use factors, it is found that CsP has the strongest explanatory power, which has a negative influence on $ESDR_C$ (Figure 6c). This study revealed that policy factors have a minor and negative impact on $ESDR_C$ (Figure 6b).

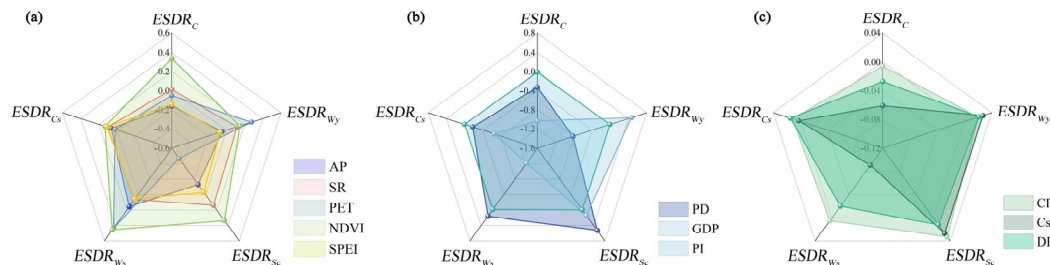


Figure 6. The influence of natural factors (a), land use factors (b), and socio-economic factors (c).

4. Discussion

4.1. Spatio-Temporal Characteristics of Supply–Demand Balance

This study revealed significant spatial heterogeneity in $ESDR_{Wy}$ and $ESDR_{Ws}$ across the Ulanbuh Desert, aligning with established patterns of ESDR distribution in arid ecosystems [60,61]. Notably, the overall $ESDR_{Wy}$ in the study area shows a deficit status, which contrasts with the surplus reported in the upper Ganjiang River basin [6]. This discrepancy may be due to distinct driving mechanisms. Desert ecosystems exhibit $ESDR_{Wy}$, primarily regulated by precipitation fluctuations [52,62,63]. The high permeability of its sandy soils facilitates rapid infiltration, resulting in substantial subsurface runoff [64,65], leading to insufficient Wy supply. Conversely, $ESDR_{Wy}$ in the upper Ganjiang River basin shows greater sensitivity to land use changes [6], highlighting the unique water–energy contradictions in arid regions. $ESDR_{Wy}$ surpluses occurred in the eastern Ulanbuh Desert, correlating with enhanced surface water recharge from ecological water diversion projects and aligns with the implementation of Yellow River Basin ecological security strategies [66]. $ESDR_{Ws}$ in the southwestern part of the study area showed deficits, which is mainly due to the high distribution of mobile dunes, semi-fixed dunes, and fixed dunes [36]. Meanwhile the northeastern part showed a surplus status, attributed to the vegetation restoration that significantly decrease sediment transport demand through effective sand fixation [67]. Enhancing Ws and Sc effectively reduces wind and water erosion, improves soil environmental stability, and thereby contributes to the enhancement of Cs.

The trends of ESDR in the Ulanbuh showed significant spatial differentiation, corroborating previous arid region studies [68,69]. $ESDR_{Sc}$, $ESDR_{Ws}$, and $ESDR_{Cs}$ all exhibit an increasing trend in the northeastern of Ulanbuh, potentially driven by the synergistic photovoltaic–agropastoral systems that enhanced ecological functions and sustainable productivity [70]. Firstly, the sand-control function of photovoltaic components and the cultivation of suitable plants can effectively reduce wind erosion [71–73]. Additionally, planting elevates regional vegetation coverage by approximately 75%, substantially enhancing carbon sequestration capacity [70]. Furthermore, root system development in eco-agropastoral systems reinforces soil structure, improving soil aggregate stability and erosion resistance [74,75], leading to an increase in $ESDR_{Sc}$. These observed changes in the ecosystem service supply–demand relationships have profound implications for the Ulanbuh Desert ecosystem and its surrounding environment. The surplus status and increasing ESDR for Ws, Sc, and Cs in the northeast indicate that enhanced vegetation cover reduces water and wind erosion while increasing carbon storage. Research has shown that

the deficit status of W_y exacerbates water stress on natural vegetation, limits ecological restoration potential, and may create feedback loops that further degrade ecosystem resilience [67]. The surplus of W_s and the increase in the $ESDR$ reduced sediment input to the Yellow River, reflecting a significant improvement in the effectiveness of regional W_s [76].

4.2. Multiple Factors Drive the $ESDR$

This research identified both natural and socio-economic factors as significant contributors to the overall supply–demand balance, aligning with the conclusions of existing research [6,77]. From the perspective of natural factors, NDVI emerged as the most influential positive factor affecting the $ESDR_C$, primarily through its regulatory effects on $ESDR_{Sc}$, $ESDR_{Ws}$, and $ESDR_{Cs}$. Vegetation roots enhance soil stability, thereby improving erosion resistance and reducing the amount of soil erosion [78]. Meanwhile, vegetation is identified as a primary force against windbreak and sand fixation, mitigating the demand for W_s by attenuating near-surface wind speeds through canopy structure modification [36,42,79]. Furthermore, vegetation enhances C_s supply by effectively capturing atmospheric CO_2 and storing it as organic matter in soils [80].

Desert ecosystems, located in arid and semi-arid regions, are particularly sensitive to climatic conditions, with the availability of water resources being a key factor affecting the balance of ES. Our study revealed that precipitation is a significant negative climatic factor impacting the $ESDR_C$ in the study, predominantly influencing the $ESDR_{Wy}$, $ESDR_{Sc}$, and $ESDR_{Cs}$. Insufficient precipitation coupled with high evapotranspiration rates are identified as the primary causes of regional drought [81]. Although regional precipitation has exhibited a fluctuating upward trend, the evapotranspiration rate demonstrates a more pronounced increase. Furthermore, precipitation remains relatively low, while evapotranspiration levels are substantially high. (Figure 7). The slight rise in precipitation proves insufficient to compensate for water loss caused by high evapotranspiration rates [82], consequently exacerbating the deficit in $ESDR_{Wy}$. Scholars have found that due to cyanobacterial crusts, carbon emissions from crusted soils in the Ulanbuh Desert increase with rising precipitation, thereby reducing the carbon sequestration capacity in the desert [83]. Moreover, intense rainfall leads to increased actual soil erosion, which in turn leads to a substantial rise in the Sc demand [84].

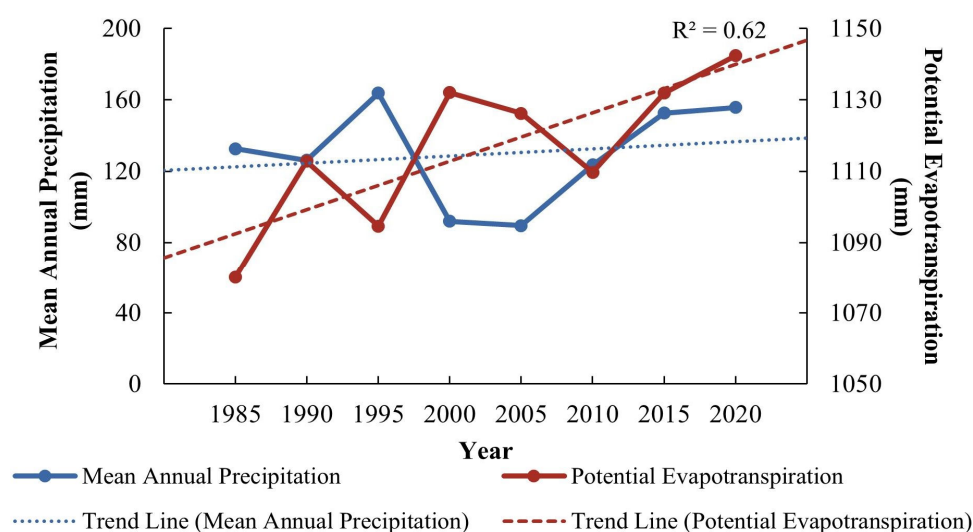


Figure 7. Mean annual precipitation and potential evapotranspiration and their trends in the Ulanbuh Desert from 1985 to 2020.

Socio-economic factors also cannot be ignored. The research analysis identified GDP and population density as negative influences to the $ESDR_C$. These factors jointly reflect

human activities intensity. Enhanced human interventions elevate ES demand, thereby disrupting the balance between supply and demand [85]. GDP escalation often correlates with higher energy consumption, particularly from the combustion of fossil fuels, which elevates CO₂ emissions. This process simultaneously rises Cs demand and lowers the supply–demand ratio [86,87]. Population density primarily affects the $ESDR_C$ through its impact on Wy and Cs demand. Increased population density leads to heightened water consumption for both production and domestic purposes, resulting in greater exploitation and depletion of water resources and, consequently, an augmented demand for Wy [88]. Furthermore, higher population density is linked to increased carbon emissions, which in turn amplifies the Cs demand [14].

4.3. Ecological Conservation Strategies in Response to Declining $ESDR$

The study revealed significant supply and demand declining in S_c , W_s , and C_s , with the NDVI identified as the primary natural factor. Therefore, enhancing vegetation coverage can effectively alleviate mitigate the rate of decline in the $ESDR_{S_c}$, $ESDR_{W_s}$, and $ESDR_{C_s}$. In arid regions, this is primarily achieved by planting drought-tolerant vegetation to mitigate soil erosion and sand mobility, while enhancing carbon sequestration via root biomass accumulation and litter decomposition. Furthermore, leveraging the abundant solar and wind energy resources of desert ecosystems [54], the expanded deployment of renewable energy infrastructure (photovoltaic power stations) can stabilize sand movement and fix soil carbon [89,90]. However, Wy falls short of demand in this region, and vegetation restoration may also increase water demand. Therefore, vegetation restoration in these areas must account for water resource constraints to prevent exacerbating the deficit. On one hand, regional GDP growth should drive the adoption of water-saving irrigation technologies, reducing water consumption per unit of GDP and improving water use efficiency through optimized vegetation spatial patterns. On the other hand, the geographical advantage of the Ulanbuh Desert near the Yellow River should be utilized to implement ecological water diversion projects, replenishing regional water resources. These integrated strategies promote synergistic energy–industry–ecological development, supporting the sustainable governance of desert ecosystems.

4.4. Limitation and Prospect

This research evaluated the ES of desert ecosystems by examining both supply and demand aspects and analyzed the driving factors affecting $ESDR_C$, providing a basis for the ecological protection and restoration of desert ecosystems. However, there are still some limitations in our research. Firstly, the four selected services do not fully represent the ES of the region. Future studies could consider a broader range of ES, such as biodiversity and tourism. Additionally, when calculating the composite supply–demand ratio, we employed an equal-weighting method without objectively quantifying the weights among the supply–demand ratios of various indicators. Future research can explore and apply more objective weighting methods, such as the analytic hierarchy process (AHP) incorporating expert knowledge, principal component analysis (PCA), or entropy weighting based on indicator variability, to better reflect the relative importance of different ES in the desert context. Secondly, a more comprehensive set of socio-economic factors, such as the effect of livestock density and urbanization rate on ES, should be considered in the future. Lastly, future research should prioritize utilizing higher-resolution data sources (e.g., Sentinel-2 at 10–20 m, or Landsat at 30 m) and adapting models capable of effectively integrating and processing such finer-scale data to capture the heterogeneity of desert ecosystems more accurately.

5. Conclusions

Through the analysis of ES (Wy, Sc, Ws, and Cs) supply and demand dynamics in the Ulanbuh Desert from 1985 to 2020, this study delineated the driving factors influencing them. Specifically, the $ESDR_{Wy}$ showed insignificant change, while the overall trend for $ESDR_{Cs}$ was downward. The areas showing an increasing trend in $ESDR_{Sc}$ are concentrated in the northeastern and southwestern portions of the study area. The $ESDR_{Ws}$ shows an increasing trend in the northeastern area. The $ESDR_C$ also exhibited a downward trend, with a supply–deficit status emerging in the southwestern sector. The multifactorial analysis identified NDVI, solar radiation, and precipitation as dominant natural regulators, coupled with GDP and population density as primary anthropogenic driving factors. Addressing the issue of regional supply and demand deficit necessitates the rational planning of land use structure and layout tailored to each region, as well as the formulation of policies that align with regional ecological characteristics, thereby ensuring harmonious development between ecology and socio-economy. It is crucial to incorporate policy implementation and more granular changes over time into our future research endeavors.

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Abbreviations

The following abbreviations are used in this manuscript:

ES	Ecosystem services
Wy	Water yield
Sc	Soil conservation
Ws	Windbreak and sand fixation
Cs	Carbon sequestration
PDA	Panel data analysis
ESDR	ES supply–demand ratio
$ESDR_{Wy}$	Wy supply and demand ratio
$ESDR_{Sc}$	Sc supply and demand ratio
$ESDR_{Ws}$	Ws supply and demand ratio
$ESDR_{Cs}$	Cs supply and demand ratio
NDVI	Normalized difference vegetation index
GDP	Gross domestic product
SPEI	Standardized precipitation evapotranspiration index

Appendix A

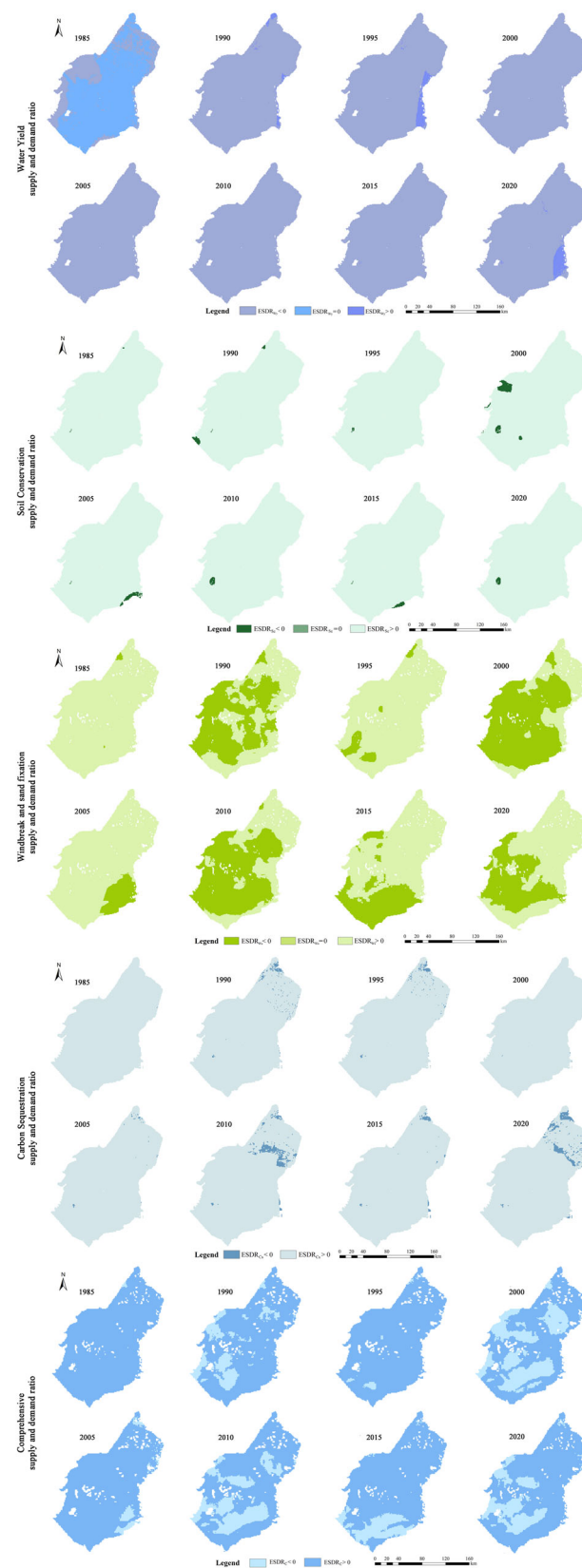


Figure A1. Spatial and temporal distribution of $ESDR_{WY}$, soil conservation $ESDR_{SC}$, $ESDR_{WS}$, $ESDR_{CS}$, and $ESDR_C$ in Ulanbuh Desert from 1985 to 2020.

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