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Journal

Habitat International, 166

ISSN

0197-3975

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et al.

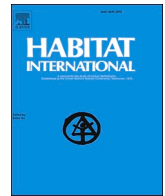
Publication Date

2025-12-01

DOI

10.1016/j.habitatint.2025.103567

Peer reviewed



Understanding the nonlinear trade-off relationship to optimize urban-rural ecosystem services: a case study in arid and semi-arid region, China

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ARTICLE INFO

Keywords:

Ecosystem services
Nonlinear trade-off
Urban-rural gradient
Production possibility frontier
Inner Mongolia

ABSTRACT

In arid and semi-arid regions, the potential for ecosystem service trade-offs creates challenges for sustainable ecosystem management due to the spatially varying ecological characteristics along the urban-rural gradient. However, the nonlinear dynamics of these trade-offs remain poorly understood. In this study, five key ecosystem services were assessed—carbon sequestration, food production, water yield, soil retention, and windbreak and sand fixation, using remote sensing inversion and ecosystem assessment models. The production possibility frontier (PPF) framework was introduced to systematically examine the heterogeneity in nonlinear trade-off relationships across urban, urban-rural fringe, and rural areas in Inner Mongolia from 2000 to 2019. The results showed that all ecosystem services increased to varying degrees, while five out of ten pairs of ecosystem services exhibited significant trade-offs. The highest trade-off intensity occurred between soil retention and windbreak and sand fixation service, with values of 0.52 in rural area and 0.64 in the urban-rural fringe. Notably, trade-off relationships and intensities varied across spatial contexts and the strongest trade-off intensity observed in urban-rural fringe areas. Our study introduces a novel PPF-based framework to explicate heterogeneous nonlinear trade-off relationships along the urban-rural gradient and underscores the significance for targeted policy interventions adapt to these spatial differences in arid and semi-arid regions, thereby advancing theoretical insights for coordinating urban-rural development globally.

1. Introduction

Arid and semi-arid region covers 41 % of Earth's terrestrial area and support over one-third of the global population (Gaur & Squires, 2018; Wickens, 1998). These ecosystems provide vital services including climate regulation, water supply, food provision, and soil erosion (Ahlström et al., 2015; Bardgett et al., 2021; Li et al., 2021). However, they are especially susceptible to degradation and desertification (Bernardino et al., 2025; Easterling et al., 2000; Huang et al., 2018; Li et al., 2023). Despite numerous management efforts aimed at mitigating natural disaster risks, their effectiveness in restoring multiple ecosystem functions across urban-rural areas remains limited (Lewinska et al., 2023; UN, 2019; Yamanoshita, 2022). Understanding the complex relationships between ecosystem services is crucial for predicting ecological conflicts in coupled human-natural systems and for optimizing ecological restoration planning to achieve the integrated

urban-rural development in arid and semi-arid regions.

Ecosystem services refer to as the benefits humans derive, directly or indirectly, from natural ecosystems, which are crucial for well-being and survival (MA, 2005; Costanza et al., 1998; Lyu et al., 2024). This concept not only facilitates the integrated analysis of natural and socioeconomic systems but also emphasizes the importance of harmonious development between human and natural ecosystems, making the maintenance and enhancement of ecosystem services a key objective in ecosystem management (Bennett et al., 2009; Castro et al., 2014; Liu et al., 2022; Yu et al., 2025). Ecological processes, such as land use and climate change, drive interactions among ecosystem services (Qu et al., 2024; Zheng et al., 2019). These interactions give rise to both trade-offs and synergies that warrant careful consideration (Zheng et al., 2022). A trade-off is defined as a situation in which an increase in one ecosystem service may lead to a reduction in others, whereas synergy emerges when multiple ecosystem services benefit simultaneously (Lyu et al.,

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<https://doi.org/10.1016/j.habitatint.2025.103567>

Received 30 March 2025; Received in revised form 25 July 2025; Accepted 24 August 2025

Available online 13 September 2025

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2024). For example, a trade-off may arise when water quality declines as a result of the increased agricultural production driven by nitrogen utilization (Lal, 2013). By revealing the trade-off and synergy relationships, which demonstrate how increasing certain services inevitably leads to declines in others, policy makers and stakeholders gain a transparent, evidence-based framework to evaluate competing objectives, prioritize actions, and craft balanced policies that optimize both ecological and social outcomes (Cheng et al., 2022; Cruz-Garcia et al., 2017; Zhang et al., 2025a, 2025b).

Most studies employ conventional mathematical models to analyze ecosystem service relationships by calculating pairwise correlations, thereby focusing primarily on linear associations (Cheng et al., 2022; Wang et al., 2015; Zhao and Pan, 2022). Nonetheless, real-world ecosystems often exhibit thresholds and feedbacks that render these interactions disproportionate: small increases in one service may have negligible impacts on others until a tipping point is reached, after which further gains trigger abrupt, large declines in other services (Hong et al., 2024; Howe et al., 2014). This phenomenon constitutes a non-linear trade-off relationship among ecosystem services. Ecological threshold effects, saturation-driven diminishing returns, and interspecific competition can push these relationships past critical thresholds, causing abrupt shifts in slope and producing complex, curved correlations rather than simple linear trends (MA, 2005). For example, reforestation in arid regions can boost carbon sequestration but reduce water conservation once ecological resilience thresholds are exceeded (Albrich et al., 2018). In degraded ecosystems, striving to maximize service supply may even cause severe ecosystem collapse (Huebner, 2020). Understanding the nonlinear relationships among services is crucial for guiding sustainable management and maintaining regional ecosystem health. To detect the nonlinear trade-offs, dependencies and their temporal dynamics, recent studies employed a range of methods, including constraint-line classification, Bayesian networks and wavelet coherence (Cheng et al., 2022; Ding & Jian, 2024; Li et al., 2024a, 2024b). Beyond these tools, the Production Possibility Frontier (PPF) framework, rooted in economic theory, has been applied to delineate the boundary of feasible resource allocations, facilitating the identification of optimal combinations of ecosystem services under multiple objectives and constraints (Cord et al., 2017; Fang et al., 2024; Peng et al., 2024). Hence, advancing the comprehension of nonlinear relationships is imperative, and the PPF framework provides a robust approach for this purpose.

Previous studies have revealed spatial variation in ecosystem services between urban and rural areas (Fang et al., 2024; Zhang et al., 2021). In addition to these spatial differences, the nonlinear trade-offs also vary along the urban-rural gradient (Liu et al., 2019; Wang et al., 2022a, 2022b). Accounting for the variations in nonlinear trade-offs has been shown to enhance planning processes and improve human well-being for both urban and rural residents (Radford, 2012). Research investigating trade-offs and synergies among ecosystem services has been conducted at multiple spatial scales, from provincial to community levels (Jiang et al., 2020; Krsnik et al., 2023; Lin et al., 2024; Wang et al., 2022b). However, most studies treated the study area as a whole or neglected the complex and nonlinear human-environment interactions specific to different urban-rural zones, and few considered the variations along the urban-rural gradient. To address this gap, this study evaluated ecosystem services and their nonlinear relationships across the urban, urban-rural fringe and rural areas, thereby providing foundational evidence for sustainable urban-rural development (Wu, 2021).

As a typical arid and semi-arid region, Inner Mongolia serves as a crucial ecological security barrier, hosting diverse yet fragile and sensitive ecosystems, including extensive forests, grasslands, farmlands, deserts, and sandy lands (Wang et al., 2023; Zhang et al., 2020). Over the past decades, its ecological environment has gradually deteriorated due to intense land use, excessive urban-rural disparities, and unexpected climate change, leading to a significant decline in the supply of ecosystem services and increased trade-offs, which hinder coordinated urban-rural development (Wu et al., 2025; Zhou & Shi, 2022). However,

it is still unclear for the difference in ecosystem service relationships across urban to rural areas.

To address the challenge of characterizing complex relationships among ecosystem services along the urban-rural gradient in arid and semi-arid regions worldwide, this study developed a PPF-based framework and took the Inner Mongolia as a case study area. In this study, the spatiotemporal dynamics of five critical ecosystem services were mapped and quantified. Then, trade-off and synergy relationships among these services were revealed across urban, urban-rural fringes and rural areas. Finally, based on these trade-off relationships, the PPF method was applied to assess nonlinear relationships and quantified the trade-off intensities. The findings offer valuable guidance for prioritizing ecosystem services improvement and emphasize the importance of implementing ecosystem management policies across the urban-rural gradient in arid and semi-arid regions.

2. Material and methods

2.1. Study area

This research was carried out in the Inner Mongolia Autonomous Region, covering an area of $118 \times 10^4 \text{ km}^2$. Inner Mongolia is located in north China, bordering Mongolia in the north (Fig. 1). The elevation is above 1000m in most areas, with plateaus in the south, mountains in the northeast and plains in the east, and the Yellow River runs through the province from the south. Inner Mongolia has a temperate continental monsoon climate, with hot, humid summers and cold, arid winters. Annual temperatures range from -3.8 to 11.4°C and precipitation from 20.0 to 751.1 mm. Vegetation shifts from desert steppe in the southwest to typical steppe, forest steppe, and forest in the northeast, reflecting its arid-semi-arid conditions and fragile ecosystems. As a major sandy-land and desert region, Inner Mongolia experiences severe wind and water erosion (Zhu et al., 2024). It is also one of the most vital commodity grain bases in China, with corn, wheat, and oil crops (such as soybean) as the main crops cultivated in this region. With its abundant natural resources and agricultural and livestock products, Inner Mongolia shoulders the responsibilities of national ecological barrier and food security (Shen et al., 2023). In the past two decades, Inner Mongolia has developed rapidly, with its GDP rising from 0.15 trillion CHY in 2000 to 1.73 trillion CHY in 2019. The area of built districts increased from 593 km^2 in 2000 to 998 km^2 in 2020 (increase by 68 %). Spatial differences in land use compositions and biophysical characteristics are obvious between urban and rural areas in Inner Mongolia (Fig. 1), directly determining the capacity of the landscape to provide ecosystem services. These differences have contributed to landscape imbalances and widened the wealth gap in this typical arid and semi-arid region (Kong et al., 2025; Yi et al., 2025). Moreover, extreme weather risks, intensive agricultural use, and rapid urbanization driven by climate change and human activities have led to substantial losses of ecosystem services, intensified trade-offs, and exacerbated landscape inequality (Chang et al., 2024; Hu et al., 2023; Wu et al., 2022).

2.2. Data sources

The data comprises meteorological, socioeconomic, and statistical Geographic Information System (GIS) data (including foundational geographical data, remote sensing inversion data) for Inner Mongolia in 2000, 2005, 2010, 2015, and 2019. Prior to analysis, all data were reprojected to the Krasovsky_1940_Albers coordinate system and resampled to a uniform spatial resolution of 1 km. More detailed data descriptions and sources are provided in Appendix A (Table A.1).

2.3. Methods

2.3.1. Method framework

The steps to understand the nonlinear ecosystem service trade-offs

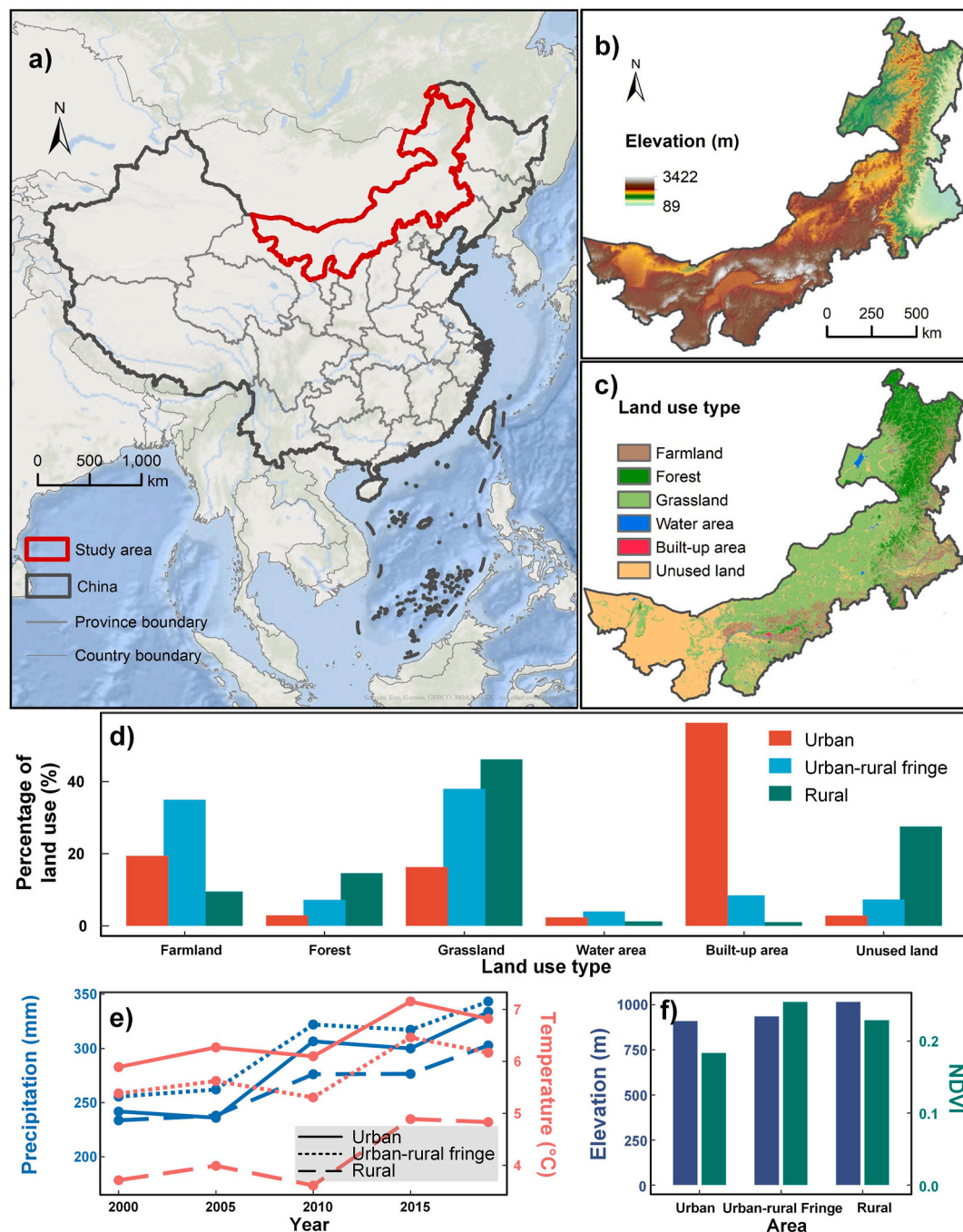


Fig. 1. Overview of study area and biophysical characteristics. The overview of the whole study area: (a) location, (b) elevation, and (c) land-use types in 2020; biophysical characteristics across urban, urban-rural fringe and rural areas: d) percentage of land use types; e) precipitation and temperature; f) elevation and Normalized Difference Vegetation Index (NDVI).

across urban-rural areas are as follows (Fig. 2):

Step 1: Identify the urban-rural areas. Based on the county-level urban boundary, the urban, urban-rural fringe, and rural areas of Inner Mongolia from 2000 to 2019 were identified.

Step 2: Quantify the dynamic of ecosystem services. The spatiotemporal patterns of five key ecosystem services in Inner Mongolia were quantified and analyzed.

Step 3: Investigate the trade-off or synergy relationships among ecosystem services. According to correlation analysis, trade-off or synergy relationships were investigated through urban-rural areas.

Step 4: Understand the nonlinear trade-off relationships. The PPF curve was used to analyze the nonlinear relationships and the intensity of ecosystem service trade-offs.

2.3.2. Identification of urban-rural area

For this study, urban is defined broadly as a large settlement with high population density and well-developed infrastructure. Rural is defined as small non-urban agglomerations with low population density, including agricultural and forestry regions (Cattaneo et al., 2021). Urban-rural fringes are transitional zones located between urban and rural regions. Using urban boundaries and buffer analysis, the urban-rural fringe areas were classified in Inner Mongolia (Peng et al.,

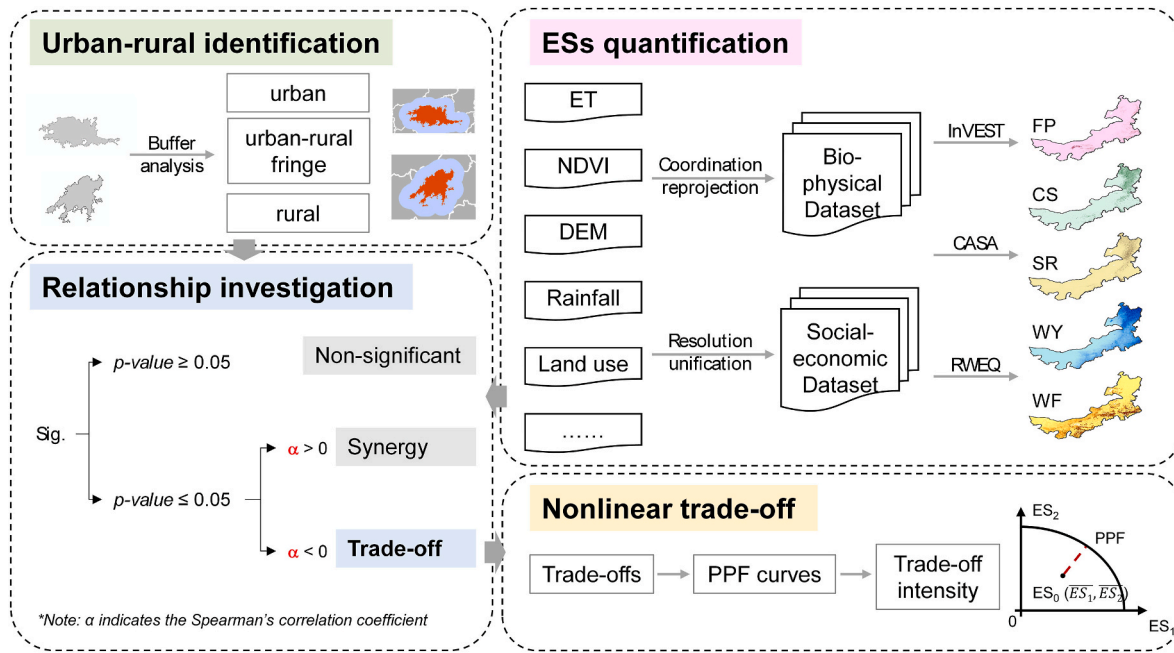


Fig. 2. The flowchart of the exploration of the nonlinear trade-off relationship across urban-rural areas. ET: Evapotranspiration; NDVI: Normalized Difference Vegetation Index; DEM: Digital Elevation Model; CS: Carbon Sequestration, FP: Food Production, SR: Soil Retention, WY: Water Yield, WF: Windbreak and sand Fixation.

2018). Administrative points and urban boundary data were used to identify the county-level urban areas. Next, a buffer zone from the urban boundary to the outside was defined as the urban-rural fringe. Urban levels were classified based on population size to determine appropriate buffer distances: for megacities with populations exceeding 5 million (not applicable in Inner Mongolia), the buffer distance was set at approximately 10–20 km; for large cities (1–5 million), 3–8 km; for medium cities (500,000–1 million), 1–3 km; and for other cities (under 500,000), 1 km (Fang et al., 2023; Peng et al., 2018). The rest of the regions were defined as rural areas.

2.3.3. Quantification of ecosystem service

As the domain ecosystems, grassland and forest carbon sinks play most important roles to absorb the atmospheric CO₂. Inner Mongolia, a principal agropastoral zone in China, providing substantial quantities of grain, meat and dairy product. However, the extensive desert and sandy lands in this region result in significant soil loss—driven by both wind and water erosion—and the scarcity of water resources. Guided by the Millennium ecosystem assessment (MA, 2005) framework and the priorities of arid and semi-arid regions, five representative ecosystem services are selected: carbon sequestration (CS) as a supporting service; soil retention (SR) and wind break and sand fixation (WF) as regulating services; and water yield (WY) and food production (FP) as provisioning services. The main formulas for quantifying these ecosystem services are presented below, with detailed information and equations provided in Appendix B.

2.3.3.1. Carbon sequestration. Carbon sequestration (CS) refers to carbon sequestered by terrestrial ecosystems. Biomass carbon density can be evaluated based on biomass density and carbon content. In this study, the change in carbon density from the following year is considered as the biomass carbon sequestration for the current year. Using five machine learning methods, remote sensing inversion of forest and grassland aboveground biomass was initially conducted (Cui et al., 2024), and carbon sequestration was subsequently calculated according to Eq. (1):

$$BCD_m = \sum_{i=1}^n B_{im} \times CC_i \quad (1)$$

where, BCD_m is the total biomass carbon density on territorial ecosystems in each pixel in year m ; B_{im} represents the biomass density of ecosystem i in year m ; CC_i is the carbon content in the biomass of ecosystem i , which is 0.5 for forest and 0.45 for grassland.

2.3.3.2. Food production. Food production (FP) refers to the food heat provided to human beings by terrestrial ecosystems, involving crop and livestock products. Firstly, given the significant linear correlation between the Normalized Difference Vegetation Index (NDVI) of farmland and crop yield (Hu et al., 2018), city-level statistical crop production data from yearbooks was allocated to farmland, including wheat, corn, and oil crops. Then, livestock products (including pork, beef, mutton, and cow milk) were spatially assigned based on the livestock distribution, as described by Eq. (2). Finally, to ensure a consistent representation of the yield of various products, the food supply calorific value method was employed, converting the product yields into heat value and summarizing them:

$$S_{Food} = \sum_{i=1}^n A_{ij} \times \frac{P_i}{CA_j} \quad (2)$$

where, S_{Food} is the total heat provided by food in grid cell of i within city j ; A_{ij} corresponds to the maximum value of NDVI or number of livestock in grid cell of i within city j ; CA_j denotes the sum of the maximum of NDVI or the total number of livestock within city j .

2.3.3.3. Soil retention. Soil retention (SR) refers to the ability of ecosystems to retain the soil due to rainfall-associated overland flow. SR was calculated by the sediment delivery ratio (SDR) model of InVEST, using the Revised Universal Soil Loss Equation (RUSLE) (Eq. (3)) (Renard et al., 1991). Soil retention service was estimated as the difference between potential soil loss and actual soil loss, which can be attributed to land use policy, natural resource practices, and cropping pattern planning.

$$S_{\text{Soil}} = R \times L \times S \times K \times (1 - P \times C) \quad (3)$$

where, S_{Soil} represents the supply of soil retention, R is the rainfall erosivity factor; K is the soil erodibility factor; L and S are topographic factors; P refers to the soil and water conservation measures factor; C corresponds to the vegetation cover factor.

2.3.3.4. Water yield. Water yield (WY) refers to the proxy to quantify the value of the hydrological regulation potential of the study area (Aryal et al., 2023). In this study, WY was simulated by the InVEST model, which calculated the difference between precipitation and actual evapotranspiration for each landscape unit (Pham et al., 2019), as depicted in Eq. (4):

$$S_{\text{water}} = \left(1 - \frac{AET}{P}\right) \times P \quad (4)$$

where, S_{water} is the water yield value; AET is the actual annual evapotranspiration; P is the annual precipitation. Annual precipitation and actual evapotranspiration raster data are derived from the National Earth System Science Data Center. Otherwise, the depth to root restriction data is from the article conducted by (Yan et al., 2020). The data for the plant available water fraction is derived from an empirical model based on measured data from China, calculated using soil nutrient content. The soil nutrient content is obtained from the Harmonized World Soil Database (HWSD).

2.3.3.5. Windbreak and sand fixation. Windbreak and sand fixation (WF) service is defined as the amount of sand retained by wind erosion. With its concentrated sandy land and desert, arid climate, and frequent strong winds, wind erosion has led to severe land degradation and a decline in human well-being. Therefore, as a critical ecosystem service in Inner Mongolia, WF was assessed by the Revised Wind Erosion Equation (RWEQ). RWEQ is a process-based physical model and is widely recognized for its effectiveness and reliability in quantifying wind erosion processes. WF was calculated by Eq. (5):

$$S_{\text{wind}} = S_{Lp} - S_L, \quad (5)$$

where S_{wind} is the sand fixation amount, S_{Lp} is the potential wind erosion amount, S_L is the actual wind erosion amount.

2.3.4. Ecosystem service trade-off or synergy relationships

Spearman's correlation analysis was applied to examine the correlations between pairs of ecosystem services in urban, urban-rural fringe, and rural areas at the county level from 2000 to 2019. The Spearman correlation coefficient was calculated to analyze the existence of trade-off and synergy among 10 pairs of ecosystem services, using R software. At a significance threshold of $p < 0.05$, a negative correlation indicates a trade-off, while a positive correlation indicates a synergy between ecosystem services.

2.3.5. Nonlinear trade-off relationships among ecosystem services

Production possibility frontier (PPF), also known as the Pareto curve, is an economic model that represents various combinations of maximum possible quantities of products under fixed production factors and technology (King et al., 2015). On the basis of established studies, the PPF framework was applied to examine nonlinear trade-offs and enhance the optimization of ecosystem service interactions. Using the method described in section 2.3.4, ecosystem service pairs exhibiting trade-off relationships were selected for further analysis of their nonlinear trade-off characteristics. Employing the Pareto-efficient criterion, the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) clustering was used to identify the outlier points and optimal combination points of ecosystem services which were then fitted using a polynomial function to derive the PPF across different urban-rural areas at the county level. It is expressed as a

two-dimensional smooth curve (Ding & Jian, 2024). The points on the PPF represent the counties (urban, urban-rural fringe, or rural area) of Inner Mongolia with the highest efficiency in providing both ecosystem services, which represent the ideal combination. Points below the curve are suboptimal, and the natural resources in this county are underutilized. The trade-off intensity can be expressed as the shortest distance between the PPF curve and the point of average values of two ecosystem services across counties that do not satisfy the Pareto-efficient criterion (Hu et al., 2023). Eq. (6) is used to calculate the trade-off intensity:

$$D = \min \sqrt{(x_0 - x)^2 + (y_0 - y)^2} \quad (6)$$

where, D is the trade-off intensity; x_0 and y_0 refer to the average value of two ecosystem services, respectively; x and y represent the values of the two ecosystem services at any point on the PPF curve.

3. Results

3.1. Spatial patterns of urban-rural area

In this study, urban areas indicate the center of prefecture-level cities and county-level towns. Urban-rural fringes are transitional zones located between urban and rural areas, blending urban and rural land uses while being shaped by both urban growth and rural transformation. Rural areas include rural settlements, cropland, forest, grassland, water bodies, and unused land (including Gobi, desert, barren land, wetland, etc.). Inner Mongolia comprises 103 county-level administrative areas with urban settlements spatially dispersed across the region. The urban levels were classified according to the population of urban area (Table C.1). The distribution of population level is shown in Fig. 3b. Fig. 3a illustrates the spatial distribution of urban, urban-rural fringe and rural areas. In the south, large cities are clustered around the capital, Hohhot City, which benefits from abundant water resources near the Yellow River. In the east, several mid-sized cities have emerged on the fertile northeast plain, where rich soils promoted the urban development. In contrast, other parts of the north and east are characterized by only small cities, largely due to the dominance of forest and desert landscapes.

3.2. Dynamics of ecosystem services

Under the deterioration of ecological and environmental conditions, we focused on quantifying the value of and relationships among ecosystem services across rural and urban areas. This approach provides robust scientific support for developing precise land use policies and improving the efficiency of resource management (Matios & Burney, 2017; Zhao et al., 2023).

The distribution of average values and their frequencies of five ecosystem services from 2000 to 2019 are presented in Fig. 4, showing evident spatial inconsistencies and varying change trends. Carbon sequestration (CS) and soil retention (SR) exhibited similar spatial patterns (Fig. 4a–c), with both being highest in forest and grassland areas in the east, while relatively low in the southeastern desert, central plateau, and eastern plain regions. In terms of quantity, both CS and SR showed an upward trend. The food production (FP) service was higher in the Yellow River surrounding areas and the plains in the east, but relatively lower in the central and western regions of Inner Mongolia. It is also characterized by a significant increase, with medium 1.93×10^8 kcal km^2 in 2000 and 3.95×10^8 kcal km^2 in 2019. The high-value areas of water yield (WY) were mainly located in the northeast, where forests provided high service of WY. From 2000 to 2019, the water yield in this area increased sharply (Fig. 4d). In 2000, the medium of water yield was 32.13×10^2 t km^{-2} , while in 2019 it was 65.59×10^2 t km^{-2} . Lower windbreak and sand fixation (WF) values mainly covered the southern, eastern, and northern desert areas with relative vegetation coverage. The medium of WF fluctuated, initially increasing before declining, with

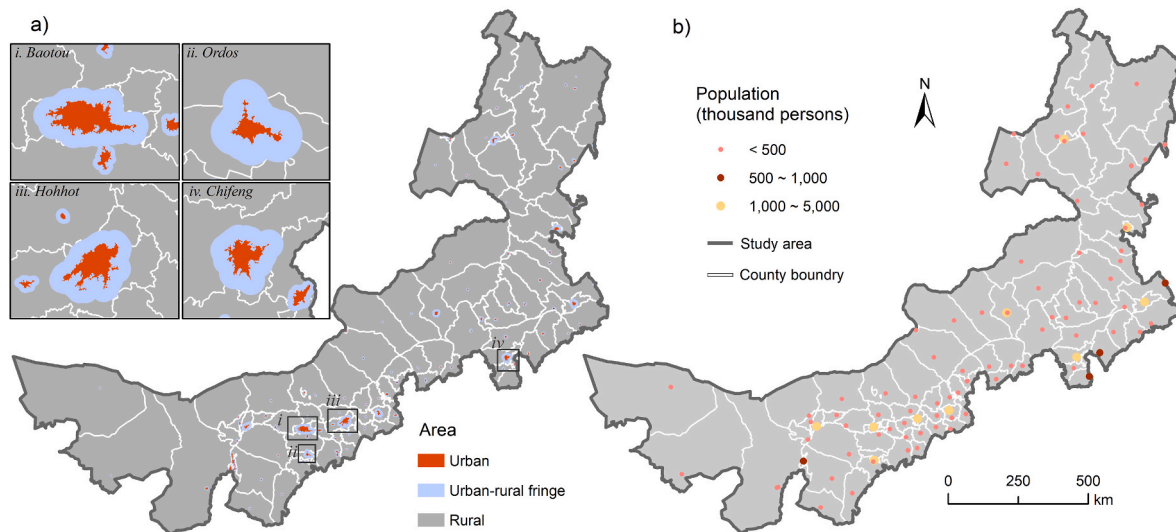


Fig. 3. Spatial distribution of (a) urban, urban-rural fringe and rural areas and (b) population at county-level administrative areas in Inner Mongolia in 2020.

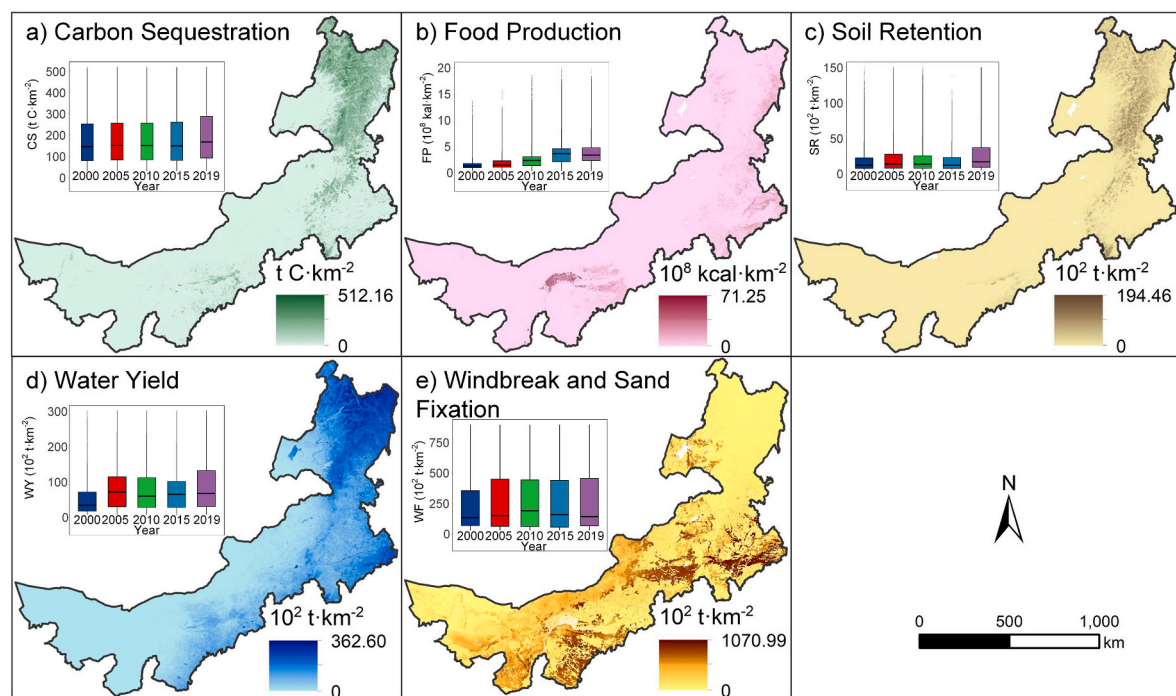


Fig. 4. Spatial distribution and statistic dynamics of ecosystem services in Inner Mongolia. The average value and box plots at the raster scale for a) carbon sequestration, b) food production, c) soil retention, d) water yield, and e) windbreak and sand fixation from 2000 to 2019.

minimal net change over the study period, starting at $134.23 \times 10^2 \text{ t km}^{-2}$ and ending at $141.96 \times 10^2 \text{ t km}^{-2}$.

Since the beginning of the 21st century, all these crucial ecosystem services across all areas have experienced significant increases, indicating the effectiveness of ecological restoration and protection strategies. However, the supply of ecosystem services exhibited significant differences across diverse areas. For instance, CS and SR were relatively low in urban-rural fringe areas. Rural areas exhibited the highest CS, primarily contributed by forests. Fortunately, despite the ongoing urbanization, the expansion in green space ensured that CS not only avoided decline but also increased from 2000 to 2019 (Table 1). CS and SR have significantly increased across all areas. Not only vegetation cover but also impervious surface has a positive effect on the soil erosion caused by wind. As the expansion of developed land in urban and urban-

rural areas, the WF can remain at a relatively high level.

3.3. Trade-offs and synergies of ecosystem services

The correlations between ten pairs of ecosystem services across urban-rural areas were presented in Fig. 5. A positive correlation indicates a synergy, while a negative correlation indicates a trade-off. Across the urban-to-rural transitional areas, the relationships between pairs of ecosystem services showed distinct and variable patterns. In urban areas, two synergy and two trade-off relationships were observed representing the least significant correlations among all areas. All the trade-offs in urban areas are related to the WF, especially WF and FP, as well as WF and WY. The most trade-offs observed in urban-rural fringe areas, WF had a trade-off relationship with all other services, and there

Table 1

Average ecosystem services in urban, urban-rural fringe, and rural areas from 2000 to 2019.

Area	Year	CS (t·km ⁻²)	FP (10 ⁸ kcal km ⁻²)	SR (10 ² t km ⁻²)	WY (10 ² t km ⁻²)	WF (10 ² t km ⁻²)
Rural	2000	12.997	0.195	2.729	22.991	152.637
	2005	12.909	0.168	3.412	34.020	179.375
	2010	16.435	0.333	3.091	43.864	185.906
	2015	12.538	0.435	2.831	39.644	188.412
	2019	22.166	0.364	5.285	52.817	201.160
Urban-rural fringe	2000	3.628	0.851	0.921	18.189	158.890
	2005	5.640	0.734	1.005	30.909	178.310
	2010	7.000	1.255	1.309	46.380	165.338
	2015	6.831	1.497	1.314	38.655	159.590
	2019	9.331	1.460	2.038	52.371	191.939
Urban	2000	0.972	0.709	0.304	6.438	139.859
	2005	2.089	0.541	0.269	11.222	148.829
	2010	2.066	0.990	0.316	20.587	140.480
	2015	1.377	1.022	0.309	14.496	134.267
	2019	2.701	1.208	0.546	28.097	180.244

was a trade-off among FP and CS. Urban-rural fringe and rural areas showed similar synergy relationships, exhibited in any two of FP, CS, and SR. In rural areas, the trade-offs were demonstrated between WF and the other three ecosystem services (CS, FP, and WY). The remaining pairs had non-significant relationships, from urban to rural areas.

3.4. Nonlinear trade-off relationship

Following the correlation analysis, five pairs of ecosystem services representing negative correlations (trade-offs relationships) were selected to further explore the nonlinear trade-off relationships. In order to avoid biases caused by dimensional differences and facilitate comparisons across diverse ecosystem services, a minimum–maximum

normalization was used to standardize all the county-level data across urban-to-rural areas to a range of 0–1 relatively. By plotting all pairs of ecosystem services of all 103 counties in Inner Mongolia for each area, outlier points were excluded, optimal boundary points were identified, and a polynomial regression was applied to derive the PPF curve (Fig. 6). The nonlinear trade-off relationship showed obviously inconsistency across urban, urban-rural fringe, and rural areas.

For CS and WF, there are significant trade-off relationships in both urban-rural fringe and rural areas. In urban-rural fringe areas, counties with low CS gathered near the ordinate showed a sharp decline as WF increased, resulting in a nearly linear PPF curve. In rural areas, along with CS increasing, WF declined rapidly at first, then gradually increased near a certain threshold. For FP and WF, trade-offs were observed across all three areas. In rural areas, WF generally decreased as FP increased. In urban-rural areas, along with FP increasing, WF declined rapidly at first, then gradually, and then rapidly again. The PPF in rural areas transitioned from gradual to steep. For SR and WF, the trade-off relationships were observed in both urban-rural fringe and rural areas. In urban-rural fringe areas, the low SR values clustered nearly ordinate, making the PPF steep. In rural areas, WF decreased sharply at first and then gradually. For WY and WF, there were significant trade-offs across diverse areas, with notable differences in their relationships. In urban areas, as WF increased, WF initially decreased sharply before gradually increasing as it approached a specific threshold. A gradually declining PPF was observed in urban-rural fringe areas. In rural areas, the synergy was observed at low levels of WY, followed by a trade-off, with a PPF curve significantly distinct from others. As WY increased, WF increased at first, then sharply decreased, and eventually stabilized at a relatively low level. Only the urban-rural fringe exhibited a trade-off relationship between CS and PF. Both CS and PF gathered at relatively low levels near the ordinate, with a sharply declining PPF observed.

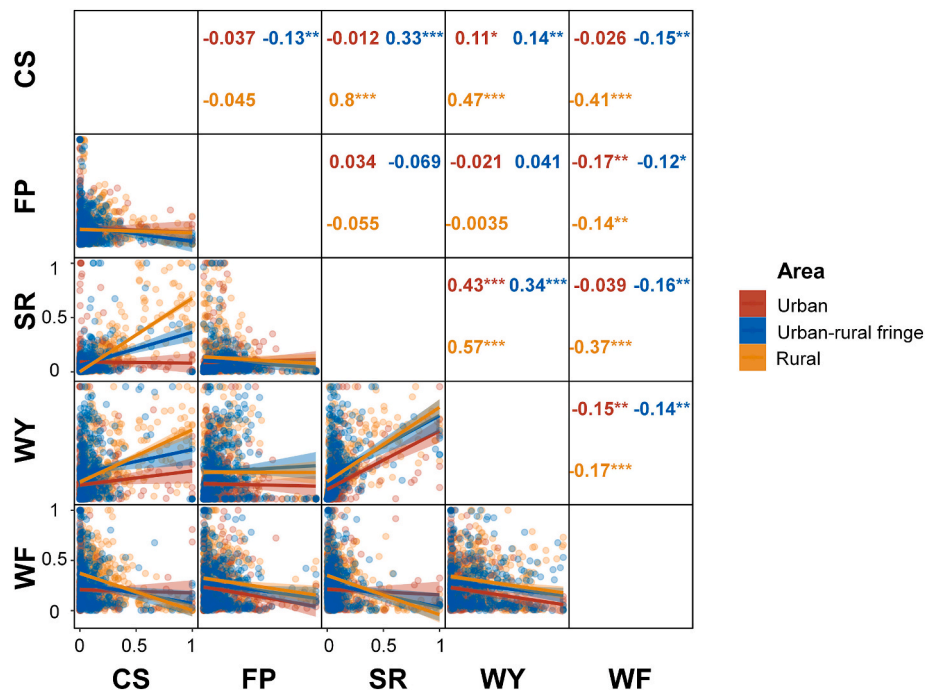


Fig. 5. Correlations and significance levels among five ecosystem services (CS: carbon sequestration, FP: food production, SR: soil retention, WY: water yield, WF: windbreak and sand fixation). The solid lines in the lower triangle represent linear regressions between paired ecosystem services, with shaded areas indicating the 99.99 % confidence intervals. The upper triangle displays Spearman's correlation coefficients, with significance levels denoted by stars: *** $p \leq 0.001$; ** $0.001 < p \leq 0.05$; * $p \geq 0.05$. Colors represent different regions: red for urban areas, blue for urban-rural fringes, and orange for rural areas. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

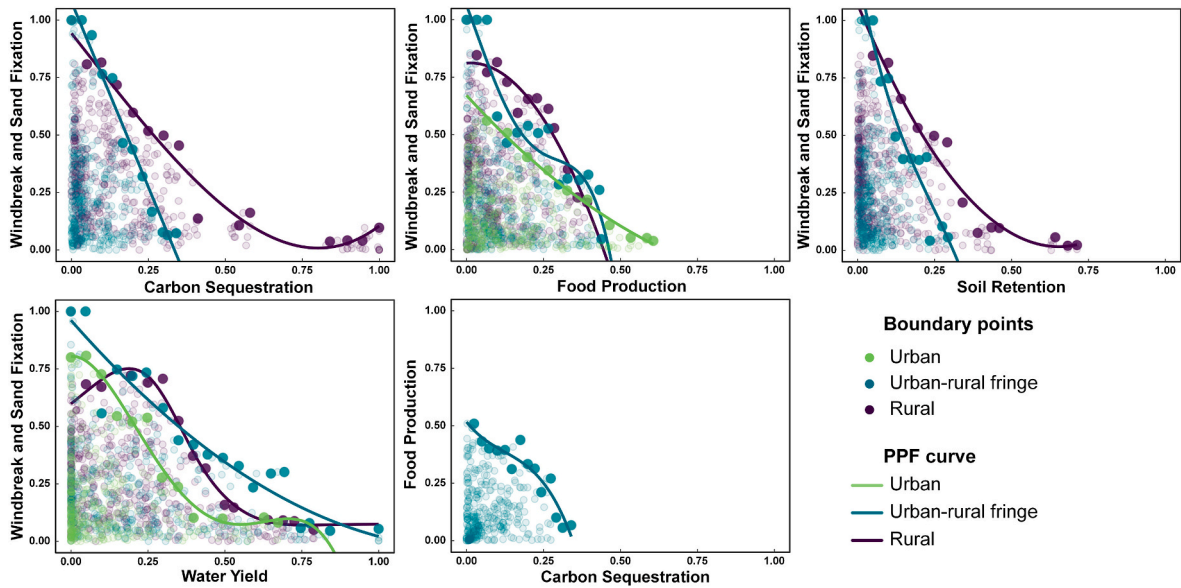


Fig. 6. Production possibility frontiers (PPF) among ecosystem services. Solid points represent boundary points, while the solid curve denotes the PPF. Colors indicate different areas: light green for urban, dark green for urban-rural fringe, and purple for rural. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.5. Trade-off intensity of ecosystem services

In a two-dimensional coordinate system, the trade-off intensity is measured as the shortest distance from the mean value points of both ecosystem services to their corresponding PPF curve (Table 2 and Fig. C1). Over the past 20 years, the dynamic characteristic of trade-off intensity showed negligible difference across urban-to-rural areas, with most pairs of ecosystem services exhibiting an increase. In rural areas, the trade-off intensity of two out of four pairs of ecosystem services—CS and WF, as well as WY and WF—increased significantly. The trade-off intensity between FP and WF increased slightly with fluctuations during this period, while that between SR and WF displayed a slight decline. In urban-rural fringe areas, the most prominent change among all ecosystem service pairs is an increase, particularly for CS and WF, SR and WF, as well as WY and WF which can be regarded as the prior areas for ecosystem service optimization. A notable finding was the consistent decline in trade-off intensity between FP and WF. Urban-rural fringe is

the only area where the trade-off relationship between CS and FP was observed, with the intensity showing a slight decline accompanied by fluctuations. In urban areas, the trade-off intensity between FP and WF exhibited a slight decline, while that between WY and WF demonstrated no significant regular change.

4. Discussion

4.1. Spatial-temporal heterogeneity of ecosystem services

The spatial heterogeneity of ecosystem services in Inner Mongolia primarily reflects land-use differences (Zhao & Pan, 2022). Vegetation cover is the main driver of carbon sequestration (CS), with extensive woodlands and grasslands in the northeast exhibiting the highest CS values. These areas, underpinned by robust root systems, also deliver high soil retention (SR) and water yield (WY). In contrast, eastern and southern Inner Mongolia, where characterize by fertile soils, flat terrain, and abundant water resources, support intensive agriculture and thus high food production (FP). Desert and sandy lands in the southeast, southwest, and northern border zones have poor soil fertility and limited precipitation and, as a result, exhibit minimal CS, FP, SR and WY. Windbreak and sand fixation (WF), which measures the reduction from potential to actual wind erosion, peaks in vegetated sandy areas of the east and north but remains low in the thinly vegetated southeast. The spatial distributions of these five key ecosystem services are broadly align with previous studies in arid and semi-arid regions of China (Dai et al., 2024; Liu et al., 2024). Zhang, Chen, et al. (2025) revealed that, as a result of ongoing ecological restoration efforts, vegetation cover increased significantly across most regions. Consistent with this trend, all five ecosystem services have exhibited quantitative growth over the past two decades.

4.2. Quantification of nonlinear ecosystem service trade-offs along the urban-rural gradient

Synergy and trade-off are widely used to describe the relationships among ecosystem services. A trade-off happens when the enhancement of one service results in the decline of another, whereas synergy occurs when the increase of one service benefits the other (Rodríguez et al., 2006). The production possibility frontiers (PPF), which integrated

Table 2
Dynamics of trade-off intensity in urban, urban-rural fringe, and rural areas from 2000 to 2019.

Area	Year	CS & WF	FP & WF	SR & WF	WY & WF	CS & FP
Rural	2000	0.3364	0.4714	0.5024	0.4367	—
	2005	0.3883	0.5296	0.6188	0.4999	
	2010	0.3852	0.4747	0.5097	0.4845	
	2015	0.4154	0.5127	0.4736	0.5211	
	2019	0.3847	0.4849	0.4991	0.4724	
	Avg	0.3827	0.4950	0.5210	0.4917	
Urban-Rural fringe	2000	0.5894	0.4327	0.5809	0.3745	0.3186
	2005	0.6166	0.4340	0.5982	0.5287	0.2945
	2010	0.6260	0.4033	0.6496	0.4473	0.2893
	2015	0.6465	0.4007	0.6753	0.4466	0.2613
	2019	0.7118	0.4169	0.6959	0.4608	0.3159
	Avg	0.6417	0.4160	0.6423	0.4514	0.2975
Urban	2000	—	0.3747	—	0.5324	—
	2005		0.4140		0.5543	
	2010		0.3347		0.5390	
	2015		0.3293		0.6043	
	2019		0.3311		0.5111	
	Avg		0.3549		0.5470	

concepts from economics, ecology, and geography, has emerged as one of the most popular methods for analyzing the nonlinear trade-off interactions among ecosystem services (Peng et al., 2024). This approach provided practical strategies to enhance regional ecosystem service management and optimization (Vallet et al., 2018). The trade-off intensity is defined as the arithmetic mean of the shortest distance between the average values of all non-Pareto-efficient option points of two ecosystem services and the PPF curve. A higher trade-off intensity indicates lower efficiency in the provision of the two ecosystem services, which is crucial for spatial planning, resource management, and policy implementation (Lyu et al., 2024).

Socio-ecological factors drive the variation in ecosystem service interactions along the urban–rural gradient, producing distinct trade-off patterns in urban, urban–rural fringe, and rural areas (Fang et al., 2024). On the one hand, resource use pressure and land use patterns vary considerably across these zones (Fig. 1d). Intensive urbanization in core urban areas leads to land use diversification and ecosystem fragmentation, which weakens linkages among services (Morri et al., 2014). In urban–rural fringe zones, expanding built-up land and intensified agricultural mechanization create intermediate fragmentation, fostering complex trade-offs as services both interact and compete. In contrast, rural areas retain more contiguous land cover, enabling stronger interdependence among ecosystem services. On the other hand, in arid and semi-arid regions, water availability exerts a dominant control on service supply, limiting potential increases and generating competition among services (Ding & Jian, 2024). In these water-limited rural landscapes, ecosystem services depend heavily on vegetation, and conflicting water demands across different service functions generate nonlinear trade-offs.

In Inner Mongolia, WF was among the most critical ecosystem services required for the benefit of residents. It is influenced by rainfall and vegetation, which are also key factors affecting CS, SR, and WY (Ding & Jian, 2024). The increase in WF suggests a widening gap between potential and actual soil wind erosion (Eq. (5)). High vegetation cover, which has been reported to increase over the past two decades, effectively reduced actual erosion and reduced potential erosion by restoring biophysical conditions, ultimately protected the soil from erosion (Fu et al., 2017; Zhou et al., 2016). Low shrubby or herbaceous vegetation is commonly employed to prevent soil wind erosion in Inner Mongolia. While their roots effectively stabilized the topsoil, their biomass limited their contribution to CS. Moreover, these plants may absorb the scarce water in arid and semi-arid regions, potentially inhibiting the growth of high-biomass vegetation. Consequently, in urban–rural fringe and rural areas, WF showed significant trade-offs with carbon sequestration and water yield services in this region, and the similar result was also revealed by Li, Ma, and Luo (2024a, 2024b) in Central Asia, another representative arid and semi-arid region. Soil water erosion predominantly occurred in the steep mountain regions of the east, whereas soil wind erosion is more prevalent in the sandy areas of the west and south. As a result, the characteristic of the spatial distribution of WF and SR differs significantly, as depicted in Fig. 4. Wind is defined as the primary factor influencing WF, while rainfall plays a crucial role in determining SR. Due to the distinct restoration regions and specific measures, WF did not directly contribute to SR, leading to a trade-off between the two ecosystem services. The Grain for Green Project, a large-scale ecological restoring initiative launched in 2000 in Inner Mongolia, has successfully converted farmland into forests and grasslands over the past two decades. Consequently, the increase in WF has led to the decline of FP, indicating a trade-off relationship between these ecosystem services.

The weakest relationships among ecosystem services were observed in urban areas, with two synergies and two trade-offs identified. However, from 2000 to 2019, the acceleration of urbanization did not lead to severe declines in ecosystem services but instead resulted in slight increases across all services, primarily due to the expansion of green spaces. The sprawl of impervious surfaces provided substantial WF, while the expansion mainly occupied the farmland and grassland

surrounding city boundaries, leading to a decline in FP and WY.

The most complex trade-off relationship was observed in the urban–rural fringe, where FP and CS also exhibited a trade-off. The area of cropland increased most significantly, largely at the expense of grasslands, which had relatively high carbon biomass, resulting in a decline in CS. Although farmland is mainly located in rural areas, the limited extent and the adoption of appropriate management practices have mitigated the carbon biomass loss in natural ecosystems. Furthermore, advancements in agricultural technology have intensified agricultural land use in this area, reducing the ecosystem's capacity to store carbon dioxide.

4.3. Implications for land use policy

With the improvement of living standards, the Chinese government has emphasized not only the importance of economic development but also the advancement of ecological civilization especially in arid and semi-arid areas. Similarly, other arid and semi-arid areas around the world should also adopt development strategies that improve ecosystem services to meet diverse human demands. Our PPF analysis framework identified Pareto-efficient points, where two ecosystem services from a “win-win” combination with minimal trade-off intensity, offering an optimal target for ecosystem service optimization in future land use planning and policy for arid and semi-arid landscape globally. Effective optimization of ecosystem services should be grounded in robust scientific principles to ensure informed and sustainable decision-making (Li et al., 2024a, 2024b):

- 1) The prioritization of ecosystem service protection should be guided by the varying intensities of trade-offs.

In arid and semi-arid areas, WF is a critical service for local communities. The effectiveness of sand fixation strategies can be reflected by the substantial increase in WF. However, these gains come at the expense of other services, as shrub and herb plantings introduced to mitigate wind erosion also compete for scarce water resources. Table 1 illustrated that the strongest trade-off intensity was observed between WF and SR in both urban–rural fringe and rural areas, with values of 0.6423 and 0.5210 respectively, indicating that soil retention should be the second-highest priority for protection in Inner Mongolia. In other arid and semi-arid regions, WF tends to be the most important service to consider due to its severe trade-offs with other services and urgent importance to local residents, and trade-off intensities should be examined to determine the corresponding priorities.

- 2) Decisions on ecological and environmental management should be adapted to the specific characteristics of diverse areas. Although all ecosystem services across various areas experienced significant increases, trade-off conditions worsened in certain cases. Understanding the dynamics of ecosystem services and their relationships forms the basis for promoting sustainability.

Urban–rural fringe areas, characterized by the most complex trade-offs, required particular attention to optimize the ecosystem services. Constrained by ecological conservation efforts and urbanization pressures, intensifying agricultural and livestock production within limited land resources has become a critical approach to enhancing food provision in these areas (Tilman et al., 2002, 2011; Zheng et al., 2022). The expansion of cropland should be restricted to appropriate areas and locations with sustainable and scientifically guided land use intensity (Ju et al., 2024). Rising human demands have driven pronounced urbanization in this region; consequently, limiting the expansion of built-up land is essential to prevent further loss of natural ecosystems, such as grasslands and wetlands.

Rural areas possess a substantial number of forests that provide significant quantities of CS, SY, and SR. Thus, strengthening forest

conservation should be prioritized. Besides, as rural areas also serve as the primary source of food calories, merely expanding forest land may cause a shortage in FP. To achieve the goals of the rural revitalization strategy, efforts should focus on enhancing the effectiveness of forests in providing ecosystem services while ensuring the protection of permanent basic farmland through coordinated management approaches. Furthermore, extensive desert and sandy lands in rural areas create an urgent demand for WF. However, elevating WF to high levels in water-limited arid and semi-arid regions can exacerbate trade-offs with other ecosystem services by increasing vegetation water use. Therefore, once WF reaches an effective threshold, management should pivot from further plantings to maintaining and reinforcing existing sand-control measures, employing alternatives such as physical barriers and fencing rather than additional vegetation in these water-scarce environments.

In urban areas, due to the weak relationships among diverse ecosystem services, measures can be implemented to enhance each service individually with limited consideration of their interactions. Given the strong provisioning capacity of urban landscapes, prioritizing the expansion of green spaces is recommended to enhance resident well-being.

4.4. Limits and future research

Taking Inner Mongolia, a typical arid and semi-arid region, as the study area, this study focused on the nonlinear relationships between carbon sequestration, food production, soil retention, water yield as well as windbreak and sand fixation service, and explored the trade-off intensities across urban, urban-rural fringe, and rural areas. However, there are some limitations that should be noted. First, due to constraints in data availability, only a limited number of key ecosystem services, which had received widespread attention, were selected. To better capture the complexity of human well-being and ecological processes, a broader range of ecosystem services should be considered. Second, although a scientifically validated relationship index was used to evaluate trade-off intensity, the spatial heterogeneity and dynamic of nonlinear trade-off relationships require further exploration. Third, the development levels and urban construction patterns may influence the relationships among ecosystem services. Thus, further analysis of the interior of the urban landscapes is necessary to reveal the specific and accurate characteristics of ecosystem service trade-offs.

5. Conclusion

Faced with the challenge of declining human well-being due to conflicts among ecosystem services, it is critical to clarify the complex nonlinear trade-offs to inform strategies for integrated urban-rural sustainable development. This study provided a PPF-based approach to analyze nonlinear trade-off relationships among ecosystem services across urban, urban-rural fringe, and rural areas. The results revealed that from 2000 to 2019, all ecosystem services showed improvement; however, trade-off intensities increased significantly over this period. The trade-offs varied along the urban-rural gradient, with the strongest trade-off intensity observed in the urban-rural fringe underscoring the need for targeted policy interventions to mitigate the ecosystem service conflicts. The challenge of balancing ecosystem services is not unique to Inner Mongolia but represents broader sustainability issues in arid and semi-arid regions globally. Understanding the spatially differentiated trade-offs is crucial for designing effective land use management strategies that promote ecological and socio-economic sustainability.

CRediT authorship contribution statement

Lihan Cui: Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Sheng Zheng:** Writing – review & editing, Supervision, Project administration, Investigation, Conceptualization. **Yufang Jin:** Writing – review & editing, Supervision,

Investigation, Conceptualization. **Zhen Shen:** Writing – review & editing, Methodology, Data curation. **Xinyu Dong:** Writing – review & editing, Methodology, Data curation. **Min Xu:** Writing – review & editing.

Data available

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This study was supported by Open Fund of State Key Laboratory of Remote Sensing Science (Grant No.OFSLRSS202309), the National Natural Science Foundation of China (Grant No.42007194) and the China Scholarship Council (Grant No.202306320561).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.habitatint.2025.103567>.

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