Study on the Coordinated Development of Urbanization Level and Ecosystem Service Patterns in Xinjiang, China

Abstract:

This study investigates the spatiotemporal coordination between urbanization and ecosystem service values (ESV) in Xinjiang, China, from 1990 to 2020. Using multi-source geospatial and socioeconomic data—including land use, GDP, population, and night-time lights—a Coupling Coordination Degree (CCD) model was employed to analyze urban–ecological dynamics. Results show a two-stage urbanization process: steady growth (1990–2005) and rapid expansion (2005–2020), especially in northern cities. Concurrently, ESV declined after 2015 due to water and forest loss from land conversion and climate change. While urbanization and ESV coordination improved until 2015, it deteriorated afterward, signaling increasing ecological stress. The findings highlight the need for integrated urban planning, ecological compensation, and sustainable land-use policies to maintain balance between economic growth and ecosystem preservation in arid regions.

1. Introduction

Urbanization reshapes socio-ecological systems and often degrades ecosystem services (ES) vital to human well-being. SDG 11 thus calls for cities that are inclusive, resilient, and environmentally sustainable.The dynamic relationship between urbanization and the ecological environment has become a critical focus in the pursuit of sustainable development.[1] Reconciling urban expansion with ecological preservation remains a global challenge, especially in ecologically fragile regions such as Xinjiang, China.

Ecosystem services (ES), both directly and indirectly derived from ecosystem functions, underpin ecological stability and human well-being.[2]. Rapid urban expansion often results in biodiversity loss, water cycle disruption, and soil degradation. Although green infrastructure and conservation efforts exist, they are frequently outpaced by urban growth in developing regions.Insight into urbanization – ESV dynamics is essential for designing land-use strategies that reconcile development with sustainability objectives. Urbanization is intrinsically linked to demographic growth, economic advancement, and land-use transformation.[3] China, experiencing one of the fastest urban transitions globally, exhibits complex urban – ecological dynamics often oversimplified by studies that overlook the bidirectional interactions between urbanization and ecosystems.

Various models have been applied to assess urbanization – ecosystem service relationships. Existing studies have employed various models—such as LMDI[4], Ordinary Least Squares (OLS) regression[5], panel data analysis[6], Geographically Weighted Regression (GWR)[7], Grey Correlation Analysis (GCA)[8]--to explore urbanization – ESV relationships.However, most emphasize unidirectional impacts and lack spatiotemporal coupling analysis, which the Coupling Coordination Degree

(CCD) model effectively addresses.[9] Therefore, this study adopts the CCD model to evaluate bidirectional urban–ecological dynamics in Xinjiang.

While models such as LMDI, OLS, panel regression, and GWR offer insights into drivers and spatial heterogeneity, they primarily address unidirectional effects, overlooking the reciprocal interactions between urbanization and ecosystem services. GCA captures variable correlations but lacks spatiotemporal depth. In contrast, the Coupling Coordination Degree (CCD) model enables integrated evaluation of interactive dynamics and coordinated development across space and time [10].

Balzan et al. (2018) and García-Nieto et al. (2018) revealed that urbanization across rural–urban and suburban gradients often diminishes both ecosystem capacity and service flows, posing challenges to sustainability.[11][12].These findings underscore the need for targeted, service-specific mitigation strategies. However, existing research on urbanization–ESV dynamics predominantly focuses on eastern China[13][14], with limited long-term, high-resolution analyses in ecologically sensitive regions like Xinjiang[15].

Xinjiang's arid climate and diverse ecosystems—from alpine zones to deserts and wetlands—make it a key region for investigating urbanization–ESV interactions. Amid rapid economic growth, it is vital to assess whether development aligns with ecological sustainability. This study applies the Coupling Coordination Degree (CCD) model, based on remote sensing and landscape data, to examine long-term spatiotemporal dynamics (1990–2020), focusing on: (1) temporal and spatial changes in ESV; (2) regional urbanization patterns; and (3) the degree of coordination between the two processes.

2. **Materials and methods**

2.1. Study area

Xinjiang (34° 25′ N–48° 10′ N, 73° 40′ E–96° 18′ E)(Figure 1), located in northwestern China, features a typical mountain–oasis–desert ecosystem comprising deserts, alpine grasslands, wetlands, and forests. Its arid climate, ecological sensitivity, and rapid urbanization make it an ideal case for analyzing urban–ecological interactions.

2.2. Date sources

This study integrates multi-source geospatial and socioeconomic data from 1990 to 2020 to assess urbanization and ecosystem service values (ESV). Land use, night-time light, and population density data were obtained from the Resource and Environmental Data Center (RESDC) of the Chinese Academy of Sciences, while GDP data were sourced from national scientific infrastructure platforms. Livestock data were extracted from the Xinjiang Statistical Yearbook (1991–2021). All datasets were resampled to a uniform 1 km resolution to ensure spatial consistency.

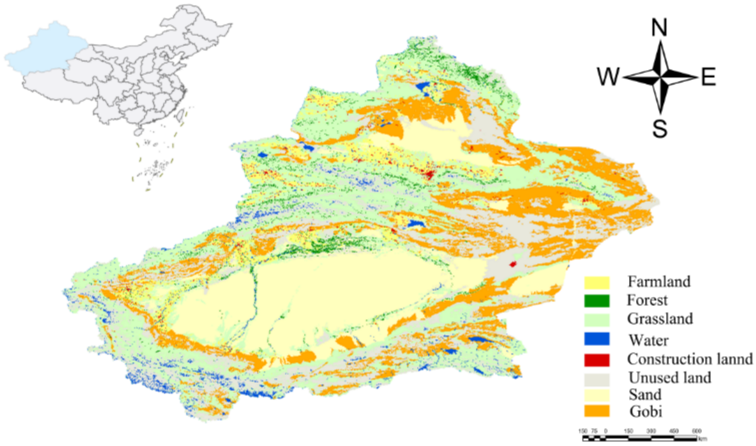

Figure 1 The Land use and land cover in Xinjiang 2020.

2.3. Methods

This study assessed the spatiotemporal evolution of ecosystem service values (ESV) and urbanization in Xinjiang from 1990 to 2020. ESV was estimated using the unit equivalent method, urbanization was quantified via a composite index, and the Coupling Coordination Degree (CCD) model was applied to evaluate their interactive dynamics.

2.3.1 Value accounting of ecosystem services

ESV was calculated using the unit equivalent method, with economic values derived from the Xinjiang Statistical Yearbook and adjusted by equivalence coefficients based on land use types. The baseline value was defined as the average net profit of the agricultural ecosystem, excluding human intervention costs. This approach follows Costanza et al.’s (1997) framework with adaptations for China’s scale-specific conditions[16][17],

2.3.2 Assessment of Urbanization Development

Urbanization was assessed through a Composite Urbanization Index (CUI) that integrates six indicators reflecting economic activity (GDP), land use (built-up and cultivated land), population distribution (density and night lights), and agricultural intensity (livestock). Indicator weights were determined using the entropy method.

$$CUI_i = \sum_{n=1}^{n} W_{ij} E_{ij}$$

In the CUI formula, each standardized indicator is weighted using the entropy method; a higher CUI value indicates a higher level of urbanization.

Table 1 Indicator of Urbanization in Xinjiang

Urbanization Index	Weight
gross domestic product (GDP)	0.1909
Building Land	0.2520

Cultivated Land	0.2024
Population Density	0.1085
Night Light	0.1288
Livestock	0.1174

2.3.3 Calculation of coupling coordination

The Coupling Coordination Degree (CCD) model quantifies the interactive strength and coordination between urbanization and ecosystem service values (ESV). In this study, CCD was used to assess their spatiotemporal dynamics in Xinjiang from 1990 to 2020, as defined by the following formulas. $C = \{\frac{f(a)\times f(b)}{\left[\frac{f(a)+f(b)}{2}\right]^2}\}^{1/2}$

$$T = \alpha f(a) + \beta f(b)$$

$$D = \sqrt{(C \times T)}$$

In the CCD model, D represents the coupling coordination value of urbanization development and ecosystem serve value, and its scale is from 0 to 1, where higher values indicate stronger coordination. α and β have the same equal to 0.5[4]. Classification thresholds for CCD stages are shown in Table 2.

Table 2 Criteria for classifying the degree of coupling coordination

Interval of D-values for coupling coordination	Level of coordination	Degree of coupling coordination
[0.0~0.1)	1	Extreme incoordination
[0.1~0.2)	2	Severe incoordination
[0.2~0.3)	3	Moderate incoordination
[0.3~0.4)	4	Mildly coordination
[0.4~0.5)	5	Nearly coordination
[0.5~0.6)	6	Barely coordination
[0.6~0.7)	7	Elementary coordination
[0.7~0.8)	8	Intermediate coordination
[0.8~0.9)	9	Good coordination
[0.9~1.0]	10	Quality coordination

3.**Results and Analysis**

3.1 Dynamic changes in ecosystem service

3.1.1 Dynamic Changes in Different Services

From 1990 to 2020, all four ecosystem services exhibited an overall declining trend, with a brief rebound around 2000 and a sharp drop in 2020. Supply and regulating services declined most significantly, while supporting and cultural services remained relatively stable. The proportional structure of ecosystem services was consistent across the period (Table 3), with higher ESVs observed in northern Xinjiang than in the south (Figure 2).

3.1.2Total changes in ecosystem service value

The evolution of ESV in Xinjiang from 1990 to 2020 can be divided into three phases: a slight decline (1990–1995), a brief peak with a 1.62% increase (1995–2000), and a continuous decline thereafter, accelerating after 2015. Land-use analysis (Table

4) shows that cultivated land contributed most to ESV gains (+1.093 billion CNY), while forests and water bodies declined significantly, with water body ESV dropping from 25.553 to 18.070 billion CNY. These trends reflect a shift toward agricultural expansion at the cost of natural ecosystems. Spatially, ESV exhibited a north–south gradient, with lower values in southern Xinjiang (Figure 3).

Table 3 The proportions of the four different types of services

Year	Supply service	Regulation service	Support service	Culture service
1990	6.58%	69.91%	19.10%	4.41%
1995	6.57%	69.93%	19.09%	4.41%
2000	6.60%	70.10%	18.91%	4.39%
2005	6.59%	70.16%	18.87%	4.38%
2010	6.58%	70.15%	18.88%	4.38%
2015	6.57%	70.23%	18.83%	4.37%
2020	6.39%	69.01%	20.15%	4.45%

3.2 Evolution of urbanization

Urbanization in Xinjiang exhibited a two-phase pattern (Figure 4): gradual growth from 1990 to 2005, primarily in northern regions, followed by rapid expansion from 2005 to 2020, radiating outward from urban hubs such as Urumqi and Yining. Although northern cities remained dominant, southern areas like Kashgar also experienced increased urban growth, indicating a trend toward regional balance.

3.3 Coupling and coordination degree of ESV and urbanization

According to Figure 5, the coordination between urbanization and ESV in Xinjiang evolved from an uncoordinated phase (1990 – 1995) to a steadily improving phase (1995 – 2015), peaking in 2015 before declining again by 2020. Spatially (Figure 6), about 80% of the region lagged in urbanization in 1990, especially near desert margins. From 1990 to 2015, both coordination levels and spatial extent improved, mainly in northern Xinjiang; however, by 2020, a sharp ESV decline became the primary factor driving overall coordination deterioration.

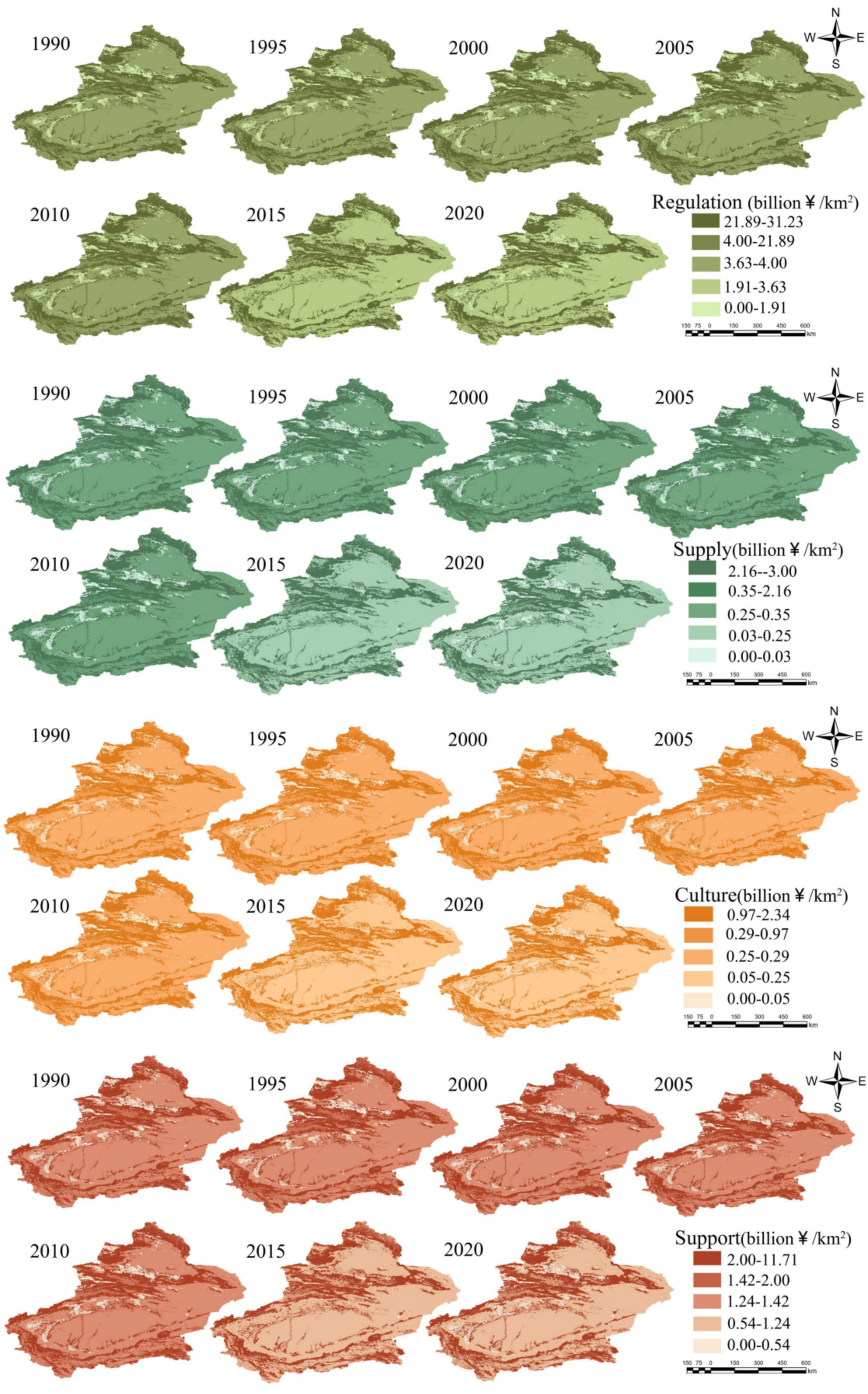

Figure2:Topographic gradient spatial distribution map

Table 4 ESV of various land uses proportions in Xinjiang（billion CNY）

year	Cultivated Land	Forest land	Grassland	Water area	Bare land	Total
1990	2.14%	6.76%	55.54%	29.33%	6.23%	87.111
1995	2.15%	6.75%	55.64%	29.22%	6.24%	86.987
2000	2.21%	7.09%	54.14%	30.44%	6.12%	88.398
2005	2.48%	7.03%	53.75%	30.62%	6.12%	88.175
2010	2.57%	7.00%	53.77%	30.52%	6.14%	87.998
2015	2.89%	6.91%	53.29%	30.79%	6.12%	87.781
2020	3.73%	5.66%	61.07%	22.80%	6.74%	79.259
Change Ratio	74.44%	-16.19%	9.95%	-22.28%	8.24%	-9.01%

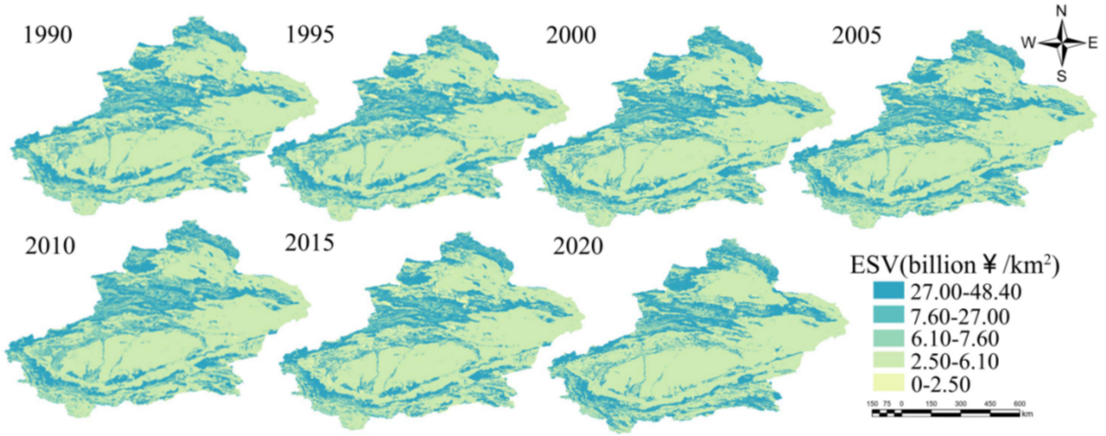

Figure 3: ESV Spatial change in Xinjiang from 1990-2020

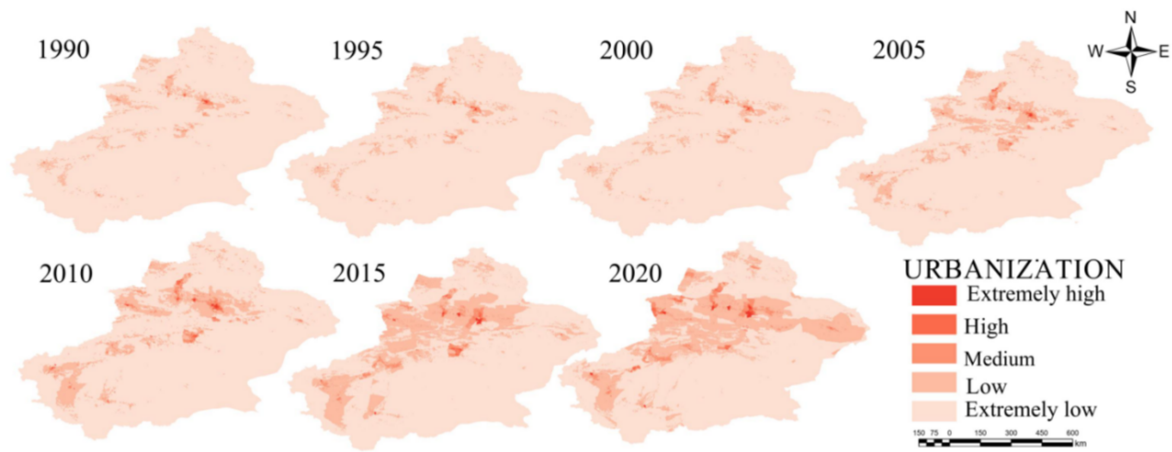

Figure 4: Spatio-temporal changes in the degree of coupling and coordination between CUI and ESV

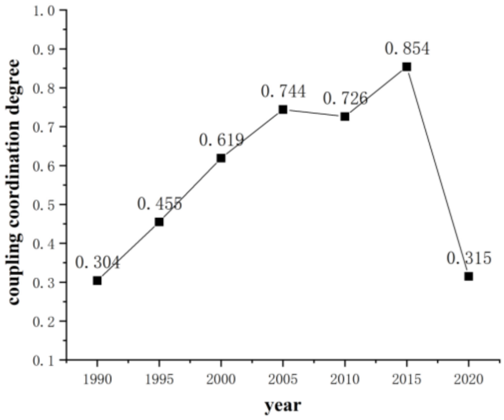

Figure 5 the degree of coupling and coordination in Xinjiang from 1990-2020

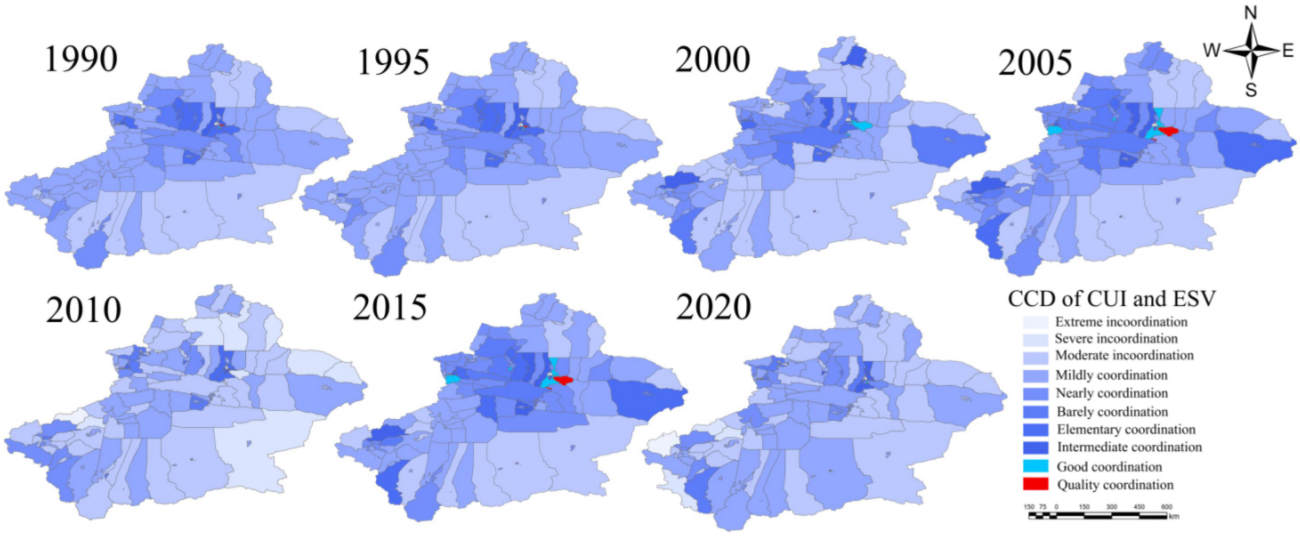

Figure 6 Spatio-temporal changes in the degree of coupling and coordination between CUI and ESV

4. Discussion

4.1 The Spatial and Temporal changes of ecosystem service value in Xinjiang

This study extends prior research by incorporating spatiotemporal analysis of ESV, highlighting spatial patterns often overlooked in earlier assessments. In Xinjiang, ESV exhibited three distinct phases from 1990 to 2020: initial decline, brief recovery, and prolonged reduction.This trend is consistent with Zhang et al. (2023), who also observed long-term ESV degradation driven by rapid urbanization in northern China during 1995 – 2015.[18] The sharp ESV decline from 2015 to 2020 was primarily driven by the loss of water bodies—such as glacial and snow melt due to global warming—and the conversion of forests and grasslands into cropland and urban land[19][Overgrazing linked to increased livestock also contributed to grassland degradation, further reducing regulating services[20].Among all ecosystem services, regulating and supporting functions contributed the most to total ESV in Xinjiang[23].

Over the past 30 years, all ecosystem services have declined, largely due to the rapid conversion of natural land into urban and agricultural uses. Regulating and supporting services suffered the greatest losses, mainly from reduced water retention, increased soil degradation, and the degradation of forests and wetlands. In southern Xinjiang—particularly around the Taklamakan Desert—ESV dropped sharply due to desertification, water loss, and glacier retreat, consistent with recent findings by Wang et al. (2024).[21]

Spatially, ESV in Xinjiang shows a clear north–south gradient, with higher values in the forest- and grassland-rich northern regions, especially the Ili River Valley and Altay Mountains. However, recent studies have noted localized ESV declines in northern Xinjiang due to land-use policies favoring agricultural and construction expansion over ecological protection.[22].

Urbanization-driven land-use shifts toward Urumqi and other northern cities have fragmented natural habitats and reduced green coverage, intensifying ecological degradation[23] Similar patterns of ESV decline have been observed in other rapidly urbanizing regions of western China, where intensive land-use transformation undermines ecosystem stability. As shown in Table 4, cultivated land contributed positively to ESV, while losses from forests and water bodies reflect a trade-off between agricultural expansion and high-value ecological services.

The sharp decline in water body ESV (from 25.553 to 18.070 billion CNY) and reduced forest-related services underscore the mounting pressure on Xinjiang's natural ecosystems. While agricultural and urban development have supported economic growth, they have simultaneously degraded key ecological functions such as water regulation and biodiversity, echoing findings from other urbanizing regions[24].

In particular, the loss of water bodies and forest ecosystems may have lasting impacts on climate regulation, water supply, and biodiversity in Xinjiang. In contrast, the Three-North Shelterbelt Program (TNSP) has created a 3,000-km green belt around the Taklamakan Desert, transforming barren areas into vegetated zones and enhancing regional ecological resilience.Spatially, ecosystem services remain stronger in northern Xinjiang, likely due to favorable climatic conditions, sustainable land-use practices, and stronger conservation intensity (Figures 2 and 4). Future research and ecological management should better account for this spatial heterogeneity to inform targeted conservation and restoration strategies.

4.2 Spatio temporal variation characteristics of urbanization

From 1990 to 2020, urbanization in Xinjiang followed a two-phase trajectory: initial concentration in the north (1990–2005), particularly around Urumqi and Yining, followed by accelerated southward expansion to cities like Kashgar and Hotan after 2005.

This shift corresponds with China's Western Development Strategy (initiated in 2000), which significantly expanded transportation infrastructure—reaching 227,900 kilometers by 2022—and reshaped regional land-use patterns by enhancing connectivity and facilitating industrial agglomeration[25][26].[15]. Urban expansion has substantially reduced cropland and grassland in peri-urban zones; in Urumqi, for instance, sprawl has encroached on agricultural land, intensifying tensions between development and food security—a trend also observed in other rapidly urbanizing regions.

4.3Coupling and coordination degree of ESV and urbanization

This study enhances the long-term understanding of human–nature dynamics in Xinjiang by identifying spatiotemporal coupling and coordination patterns between urbanization and ecosystem service value (ESV) from 1990 to 2020. The results reveal distinct temporal and spatial variations: coordination improved steadily from 1995 to 2015—driven by ecological planning and infrastructure investment—but declined sharply after 2015 due to intensified land-use conversion and rising water demand. Spatially, northern cities such as Urumqi and Yining exhibited higher coordination levels before 2015, while southern cities like Kashgar and Hotan consistently lagged due to water scarcity and weak ecological restoration.

These findings highlight the necessity of region-specific strategies to balance development and environmental protection. In ecologically fragile areas like Xinjiang, the consequences of uncoordinated urban expansion may be more severe and long-lasting than in other regions, underscoring the urgency of integrating ecological constraints into land-use planning and policy design.

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