

## Postprint: Trade-offs and Synergies of Ecosystem Service Values in Urumqi Based on the PLUS Model

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### Abstract

Land use/cover change disrupts the stable supply capacity of ecosystems, thereby threatening ecosystem services and sustainable development. Taking Urumqi City as the study area, this study simulated land use changes under multiple scenarios for 2030 based on the Patch-generating Land Use Simulation (PLUS) model, and estimated and predicted the ecosystem service value (ESV) from 1990 to 2030 as well as its trade-off and synergy relationships using methods such as the equivalent factor method and spatial autocorrelation analysis. The results indicate that: (1) From 1990 to 2020, land use in Urumqi City exhibited a “two increases and four decreases” trend. In 2030, under the inertia development scenario, all land use types except forestland follow historical evolution patterns; under the ecological protection scenario, construction land area shrinks while ecological land increases substantially; under the comprehensive development scenario, construction land area increases while ecological land area also shows an upward trend; under the key development scenario, urban construction land expansion is most intense and cultivated land degradation is severe. (2) From 1990 to 2020, the ESV of Urumqi City showed an overall “V-shaped” declining trend, with a total reduction of  $59.59 \times 10^8$  yuan. In 2030, ESV exhibits an increasing trend under the ecological protection scenario and comprehensive development scenario, while it exhibits a decreasing trend under the inertia development scenario and key development scenario. (3) Under the four development scenarios in 2030, synergy relationships dominate among various ecosystem services in Urumqi City; the “high-high” and “low-low” synergy clusters show high coincidence with the distribution of high and low ESV value areas, while trade-off relationships are sporadically distributed in local areas. The research results can provide scientific reference for territorial spatial planning and ecological security pattern construction in Urumqi City.

## Full Text

# Trade-off and Synergy of Ecosystem Service Value in Urumqi City Based on the PLUS Model

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## Abstract

Land use/cover change disrupts the stable supply capacity of ecosystems, thereby threatening ecosystem services and sustainable development. Taking Urumqi City as the study area, this research employs the patch-generating land use simulation (PLUS) model to simulate land use changes under multiple scenarios for 2030, and combines the equivalent factor method and spatial autocorrelation analysis to estimate and predict the ecosystem service value (ESV) and its trade-off and synergy relationships from 1990 to 2030. The results indicate: (1) From 1990 to 2020, land use in Urumqi City exhibited a “two increases and four decreases” pattern. Under the ecological protection scenario for 2030, the area of construction land shrinks while ecological land increases substantially; under the comprehensive development scenario, construction land area increases while ecological land area also rises; under the key development scenario, urban construction land expansion is most dramatic, with severe degradation of arable land. (2) The ESV of Urumqi City showed a “V-shaped” decline from 1990 to 2020. In 2030, ESV increases under the ecological protection and comprehensive development scenarios, but decreases under the inertia development and key development scenarios. (3) Under all four development scenarios in 2030, synergistic relationships dominate among various ecosystem services in Urumqi City, with “high-high” and “low-low” synergistic aggregation areas showing high coincidence with the distribution of high and low ESV areas, while trade-off relationships are sporadically distributed in local regions. These findings can provide scientific references for territorial spatial planning and ecological security pattern construction in Urumqi City.

**Keywords:** ecosystem service value; PLUS model; multi-scenario simulation; trade-off and synergy; Urumqi City

## Introduction

Ecosystem services refer to the various benefits that ecosystem structures and functions provide to humans, including provisioning, regulating, supporting, and cultural services [1,2]. The United Nations Millennium Ecosystem Assessment indicates that 60% of global ecosystem services are in a state of degradation or

unsustainability, threatening land use benefits and socioeconomic development [3]. Land use dynamic evolution represents a crucial manifestation of human activities transforming ecosystems, influencing ecosystem structure formation, functional supply, and spatial allocation [4,5]. With accelerating urbanization in China, regional population, resource, and environmental issues have become increasingly prominent, making the investigation of relationships between urban land use change and ecosystem services a focal point of academic research [6,7].

Ecosystem service value (ESV) serves as a quantitative response indicator of ecosystem services, capable of scientifically and accurately revealing regional ecological environmental security quality [8,9]. Since Costanza et al. [10] initiated ecosystem service research, the field has gradually matured in terms of research content, methods, scales, and simulation models. Research content primarily involves service classification, value assessment, functional monitoring, and trade-off/synergy relationships [11,12]; research methods mainly include statistical description, spatial analysis, scenario simulation, and service flow analysis [13,14]; research scales primarily cover watersheds, urban agglomerations, and administrative units [15,16]. Despite abundant research achievements on ecosystem services both domestically and internationally, certain limitations remain. Regarding study areas, current research mainly concentrates on watersheds, areas returning farmland to forest/grassland, and economically developed urban agglomerations [17,18], with limited studies on arid regions that account for over 30% of China's territory. From a research perspective, previous studies have mostly conducted static assessments based on historical statistical data, with few reports on dynamic assessments, particularly at fine scales for future scenarios [19,20]. Regarding simulation models, existing land use simulation models perform weakly in explaining driving forces of land use change and generating multi-type land use patches, whereas the patch-generating land use simulation (PLUS) model can effectively address these issues and obtain more accurate simulation results [21,22], though it has been rarely applied to predict regional ecosystem service trade-off and synergy relationships.

In recent years, national policy support and regional economic development have accelerated Urumqi's urbanization process and intensified land use pattern changes, making conflicts between economic development and ecological protection increasingly prominent. Therefore, this study analyzes the spatiotemporal evolution patterns of land use in Urumqi from 1990 to 2020, employs the PLUS model to predict future land use changes under multiple scenarios, quantifies their impacts on ESV, and explores trade-off and synergy relationships among various ecosystem services, aiming to provide decision-making support for optimal land resource allocation and ecological environment protection and restoration in Urumqi.

## 1 Study Area Overview

Urumqi City is located in the hinterland of the Eurasian continent, at the northern foot of the middle Tianshan Mountains and the southern margin of

the Junggar Basin. It governs 7 districts and 1 county, with a total area of  $1.38 \times 10^4$  km<sup>2</sup> [Figure 1: see original paper]. Surrounded by mountains on three sides, the terrain is high in the southeast and low in the northwest. As the world's most inland city far from any ocean, it has an average annual precipitation of 200 mm and belongs to the temperate continental arid climate zone. With rapid socioeconomic development, Urumqi's urbanization rate has increased substantially, reaching a regional population of  $405.44 \times 10^4$  and a gross domestic product of  $3337.30 \times 10^8$  yuan in 2020.

## 2 Data and Methods

### 2.1 Data Sources

This study utilized land use data for Urumqi City for five periods (1990, 2000, 2010, 2020, and 2030) with a spatial resolution of 30 m. Simulation driving factors were preprocessed through projection transformation, clipping, resampling, and distance analysis, and uniformly converted to a 30 m × 30 m grid. Socioeconomic data used in calculations were obtained from statistical sources, as detailed in .

### 2.2 Methods

**2.2.1 Land Use Simulation** The PLUS model improves upon the FLUS model by retaining its advantages of self-adaptive inertia competition and roulette competition mechanisms. It employs random forest algorithms to obtain development probabilities for various land use types and combines random seed generation with threshold decrement mechanisms to simulate spatial patterns of land use under top-down quantity constraints, better explaining the internal mechanisms of how ecosystems are affected by land use change from a complex systems perspective [23]. Based on Urumqi's actual conditions, we selected 12 driving factors from three perspectives: natural geography, socioeconomic conditions, and accessibility, including elevation, slope, average annual temperature, average annual precipitation, population density, GDP, distance to roads, and distance to water bodies.

According to the transfer rules of land use types, we set neighborhood weights [24], with weights of 0.8 for arable land, 0.5 for forest land, 0.4 for grassland, 0.3 for water bodies, 0.1 for unused land, and 0.6 for construction land. The simulation results show high similarity with the actual land use pattern in 2020 [Figure 2: see original paper], with Kappa and Figure of Merit values of 0.82 and 0.35, respectively, indicating good applicability of the model for this study [25].

**2.2.2 Multi-Scenario Settings** Changes in regional development needs are important factors in territorial spatial planning. Different regional development demands determine spatial development positioning. Simulating future land

use under multiple development scenarios can provide forward-looking decision-making references to assist in formulating scientific and rational land use plans, thereby optimizing territorial spatial layout and stabilizing socioeconomic development. This study designed four scenarios for 2030: inertia development, ecological protection, comprehensive development, and key development .

**2.2.3 Ecosystem Service Value Estimation** This study employed the equivalent factor method [26], revised according to local conditions of grain prices and biomass, and finalized the equivalent coefficients for Urumqi through ecosystem service sensitivity analysis.

**Revision based on grain price factor:** Considering socioeconomic heterogeneity, we used 1/7 of the economic value of grain production from farmland ecosystems to revise the equivalent factor value for ecosystem services in Urumqi. The revision method is as follows:

$$VC = \frac{1}{7} \times \frac{P \times Q}{M}$$

where  $VC$  is the economic value per unit area of ecosystem services in Urumqi ( $\text{yuan} \cdot \text{hm}^{-2}$ );  $P$  is the average market price of national grain crops in 2020 ( $\text{yuan}$ );  $Q$  is the unit area yield of grain crops in Urumqi in 2020 ( $\text{kg} \cdot \text{hm}^{-2}$ ); and  $M$  is the sown area of grain crops.

**Revision based on biomass factor:** Considering the heterogeneity of ecological spatial layout and following Xie et al.' s research [27], we determined the biomass factor for the study area as 0.35 to revise the per-unit-area ESV coefficients for Urumqi .

**2.2.4 Sensitivity Analysis** The sensitivity index is commonly used to characterize the dependence of ESV on equivalent coefficients over time, testing the rationality of the coefficients [28]. The calculation formula is:

$$CS = \frac{(ESV_p - ESV_q)/ESV_q}{(VC_{pr} - VC_{qr})/VC_{pr}}$$

where  $CS$  is the sensitivity index;  $ESV_p$  and  $ESV_q$  are the initial and adjusted ESV values, respectively; and  $VC_{pr}$  and  $VC_{qr}$  are the initial and adjusted equivalent coefficients, respectively. As shown in [Figure 3: see original paper], all  $CS$  values are less than 1, indicating that the revised coefficients are appropriate for Urumqi' s actual conditions.

**2.2.5 Spatial Autocorrelation Analysis** To explore the spatial clustering characteristics of ESV in Urumqi without being limited by administrative boundaries, we divided the study area into  $5 \text{ km} \times 5 \text{ km}$  grid cells and conducted global autocorrelation analysis for future development scenarios. We selected

the comprehensive development scenario, which aligns with Urumqi' s future urban development positioning, and performed bivariate local autocorrelation analysis in GeoDa 1.20.0 to explore trade-off and synergy relationships among various services.

### 3 Results

#### 3.1 Spatiotemporal Evolution Characteristics of Land Use

From 1990 to 2020, the main land use types in Urumqi were grassland and unused land, together accounting for 89.67% of the total area, with grassland comprising 53.28%. The primary land use conversion patterns were transitions among grassland, unused land, and arable land, with conversions between grassland and unused land being most significant .

Under the inertia development scenario for 2030, all land use types follow historical evolution patterns except forest land, which shows reverse development with an area increase of 119.62 km<sup>2</sup>, indicating certain achievements in Urumqi' s “barren hill greening project” and “garden city construction.” Under the ecological protection scenario, Urumqi emphasizes green development, with inefficient construction land being effectively consolidated, construction land area decreasing by 130.86 km<sup>2</sup>, and large areas of unused land converting primarily to forest land, grassland, and water bodies, with increases of 0.28%, 1.38%, and 0.67%, respectively. Under the comprehensive development scenario, Urumqi balances economic development and environmental protection, with construction land increasing by 3.00% (second only to the key development scenario) while unused land is maximally developed, decreasing by 589.02 km<sup>2</sup> net. Under the key development scenario, urban land use planning prioritizes economic development needs, with the most dramatic construction land expansion reaching 5.00% (441.29 km<sup>2</sup> increase), encroaching on large areas of high-quality farmland around the city.

Notably, under all future scenarios, arable land area in Urumqi continues to shrink, primarily due to topographical constraints with mountains on three sides, causing inevitable conflicts between urban infrastructure development and farmland protection in the overlapping suitable development and high-quality farmland protection zones in the western plains.

#### 3.2 Spatiotemporal Evolution Characteristics of Ecosystem Service Value (ESV)

As shown in , ESV in Urumqi exhibited a “V-shaped” decline from 1990 to 2020, decreasing slowly by  $8.84 \times 10^8$  yuan from 1990 to 2000, then sharply decreasing by  $386.46 \times 10^8$  yuan from 2000 to 2010 due to rapid socioeconomic development and large-scale construction activities under western development opportunities. From 2010 to 2020, enhanced ecological protection awareness slowed the loss to  $44.00 \times 10^8$  yuan.

In 2030, under the inertia development scenario, ESV will continue to decrease by  $8.84 \times 10^8$  yuan, indicating that previous land use patterns are unsuitable for Urumqi's future development. Under the ecological protection scenario, ESV increases by  $16.26 \times 10^8$  yuan to  $327.32 \times 10^8$  yuan, directly related to increased areas of land types with high contribution rates (forest, grassland, water). Under the comprehensive development scenario, ESV also increases by  $11.13 \times 10^8$  yuan to  $343.58 \times 10^8$  yuan, as large areas of unused land in northern Midong District are maximally developed and converted to ecological land. Under the key development scenario, ESV shows the most obvious downward trend, decreasing by  $27.96 \times 10^8$  yuan to  $342.46 \times 10^8$  yuan, as rapid construction land expansion creates enormous pressure on the ecological environment.

The spatial distribution of ESV shows consistent patterns across periods, with high values concentrated in the southwestern mountainous areas (the axis from Urumqi County to Dabancheng District, Miquan Forest Farm, Tianshan Ranch, and river/lake distribution areas) and low values in main urban areas, the Gurbantünggüt Desert in Midong District, and unused land around the Chaiwopu Lake-salt lake area in Dabancheng District [Figure 4: see original paper]. Under the inertia scenario, the distribution pattern remains similar to 2020. Under the ecological protection scenario, low-value areas at the urban fringe transform to medium-low and medium values, and ESV in northern Midong District increases due to greening activities. Under the comprehensive development scenario, development of unused land in the north causes large areas of ESV to increase while low-value areas in the main urban zone expand. Under the key development scenario, the most dramatic expansion of construction land encroaches on large areas of suburban farmland, with low-value areas in the main urban zone reaching peak levels.

### 3.3 Spatial Relationships of Ecosystem Service Trade-offs and Synergies

We used Pearson correlation analysis and Moran's I to explore trade-off and synergy relationships among ecosystem services in Urumqi. If the Pearson correlation coefficient is positive, the relationship is synergistic (stronger with larger coefficients); if negative, it represents a trade-off. If Moran's I is positive, it indicates spatial positive correlation (more significant with larger coefficients); if negative, spatial negative correlation. Correlation test results show that under all four scenarios, ecosystem services primarily exhibit spatially positive correlated synergistic relationships.

To further investigate spatial clustering characteristics, we conducted bivariate local autocorrelation analysis. As Urumqi is the political, economic, and cultural center of Xinjiang, future development should pursue triple benefits of economy, society, and ecology. Since ESV shows an upward trend under both ecological protection and comprehensive development scenarios, with the latter providing sufficient space for urban construction, we selected the comprehen-

sive development scenario as the ideal future development pattern for detailed analysis.

In 2030 under the comprehensive development scenario, various ecosystem services in Urumqi show significant spatial clustering characteristics [Figure 5: see original paper]. Synergistic relationships dominate, with “high-high” and “low-low” synergistic aggregation areas showing highly coincident distributions. The “high-high” synergistic clusters concentrate along the axis from Urumqi County to Dabancheng District, located on the windward slope of the Tianshan Mountains with abundant precipitation, where meltwater from Glacier No. 1 provides continuous water supply to the Urumqi River, resulting in high vegetation coverage. The “low-low” synergistic clusters distribute in main urban areas, northern Midong District, and around Chaiwopu Lake-salt lake, where uncontrolled urban sprawl, overgrazing, mining, and groundwater exploitation have created low-value areas. Grid cells showing trade-off relationships mainly appear at the interface between construction land and arable land, near Glacier No. 1 in southwestern Urumqi, and in snowmelt areas of the eastern Bogda Mountains –regions with fragile ecology vulnerable to human disturbance.

#### 4 Discussion

ESV is a crucial indicator of ecological security, and its accurate scientific assessment is important for regulating ecosystem functions and optimizing ecological patterns. The sharp decline in Urumqi’ s ESV from 1990 to 2020 aligns with Yang et al.’ s findings [29], indicating that urbanization and other human activities have caused unreasonable land use structures with negative effects on ecosystems, necessitating urgent adjustment of urban development strategies. Compared with static assessments of historical periods by Yang et al. [30], this study uses the PLUS model to predict future multi-scenarios, offering dynamic foresight. The multi-scenario simulation results show that scenario settings are reasonable and consistent with expected ESV changes. The comprehensive development scenario represents the optimal model for optimizing regional land use structure and alleviating ESV loss while ensuring high-quality development under ecological protection, whereas the key development scenario serves as a warning.

Regarding trade-offs between development and protection, synergistic relationships dominate ecosystem services across all scenarios, with trade-offs sporadically distributed in local areas, indicating land use competition and game relationships in some regions where conflicts exist among economic development, food production, and ecological protection. These results can provide insights for policymakers to formulate land policies balancing economic development and environmental protection. However, limitations remain. This study lacks in-depth exploration of internal mechanisms and driving forces in spatial trade-off/synergy analysis. Additionally, ecosystem service trade-off/synergy relationships exhibit spatial scale differentiation [31], and future fine-scale studies could provide more precise decision-making support for stakeholders.

## 5 Conclusions

This study dynamically simulated land use patterns in Urumqi from 1990 to 2030 under four development scenarios using the PLUS model, and quantitatively analyzed ESV and its trade-off/synergy relationships using the equivalent factor method. The main conclusions are:

- (1) Land use patterns in Urumqi changed significantly from 1990 to 2020, showing a “two increases and four decreases” trend. Under the inertia development scenario, all land types follow historical patterns except forest land. Under ecological protection, construction land area shrinks while large unused land areas convert to ecological land. Under comprehensive development, construction land increases while ecological land shows the second-largest increase, making it the ideal future scenario. Under key development, construction land expands dramatically while arable land degrades severely.
- (2) From 1990 to 2020, Urumqi’ s ESV decreased by  $59.95 \times 10^8$  yuan, showing a “V-shaped” trend. In 2030, ESV increases under ecological protection and comprehensive development scenarios, but decreases under inertia development and key development scenarios. The downward trend is most pronounced under key development, serving as a warning for Urumqi’ s future development. Under ecological protection and comprehensive development, low-value areas in northern Midong District are expected to transform into medium-high value areas.
- (3) Under all four scenarios, individual ecosystem services in Urumqi show significant spatial synergistic clustering. “High-high” and “low-low” synergistic areas show highly coincident distributions. Trade-off relationships mainly appear at the interface between construction land and arable land, near Glacier No. 1 in southwestern Urumqi, and in snowmelt areas of the eastern Bogda Mountains. Balancing development and protection remains an urgent challenge for Urumqi’ s future development.

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