

Original Paper

Research on the Spatiotemporal Patterns of Ecosystem Services
and Urban Sustainable Development: A Case Study of the
“Mid-Spine Belt of Beautiful China”

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Abstract

Urban sustainable development relies on stable ecosystem services (ESs) to coordinate human activities and natural ecosystems. This article takes the “Mid-Spine Belt of Beautiful China” as the study area, using the entropy weight method and the InVEST model, combined with multi-source data such as remote sensing, geographic, and statistical data, to quantify three categories of Sustainable Development Goal11 (economic, social, environmental) and four types of ESs (carbon storage, water yield, soil conservation, vegetation cover); establishing an evaluation framework for sustainable development applicable to the “Mid-Spine Belt of Beautiful China”. From 2015 to 2023, regional SDG11 rose generally with the lowest score in 2021; inter-city gaps shrank but regional imbalance remained. Water yield and soil conservation declined yearly, while carbon storage and vegetation coverage kept growing. Spearman correlation and MGWR uncover obvious spatial heterogeneity in the synergy and trade-off between SDG11 and ESs: four synergy pairs and three trade-off pairs declined, and economic SDGs had the strongest negative link with vegetation coverage. SOM clustering divides the study zone into four differentiated subregions with distinct ES and SDG11 performances. This work has important practical significance for maintaining the stability and sustainable development of the “Mid-Spine Belt of Beautiful China” ecosystem.

Keywords

“Mid-Spine Belt of Beautiful China”, Sustainable Development Goal 11, Ecosystem Services

1. Introduction

The rapid urbanisation of human society has led to excessive resource consumption, ecosystem degradation and worsening environmental pollution, posing an increasing threat to sustainable development at both regional and global levels. To address this challenge, the United Nations adopted the 2030 Agenda for Sustainable Development in 2015, setting out 17 Sustainable Development Goals (SDGs) aimed at promoting globally coordinated development across economic, social and environmental dimensions. Among these, “Sustainable Development Goal 11 (SDG 11: Sustainable Cities and Communities)” is regarded as the central link connecting the urbanisation process with sustainable development; its achievement is of great significance for ensuring the liveability of cities, promoting equity and inclusion, and enhancing ecological resilience. However, with the continuous advancement of China’s new urbanisation, there are significant disparities in urbanisation levels and ecological carrying capacity across regions, resulting in a complex spatial pattern of variation in cities’ capacity for sustainable development. The “Mid-Spine Belt of Beautiful China” region spans multiple provinces across eastern, central and western China, constituting a key area where dense populations, industrial agglomeration and ecological conservation responsibilities converge. Whilst serving as a national ecological security barrier, this region also faces resource depletion and ecological pressures stemming from urban expansion, energy development and industrial concentration, resulting in marked spatial disparities in urban sustainability. Although the SDGs are globally applicable, their implementation pathways require localised adaptation to account for regional characteristics. Due to factors such as data availability, administrative scales and socio-economic heterogeneity, the direct application of the global SDG indicator system at the municipal level in China has certain limitations. It is therefore necessary to construct a regional-scale localised assessment framework for SDG 11 to reveal the spatial and temporal variations in urban sustainable development.

Currently, the scientific community is utilising statistical and remote sensing data to assess regional capacity for sustainable development. For example, Yin et al. established a nested target system based on the 16 Sustainable Development Goals (SDGs) to evaluate progress towards the SDGs in plateau regions, and quantified the contribution of ecosystem carbon sequestration services to the SDGs; Liang et al. combined statistical data with remote sensing products to establish an assessment framework for sustainable urbanisation in coastal cities, conducting a spatio-temporal analysis of the sustainability of urbanisation on Hainan Island; Yang et al., drawing on data from statistical yearbooks, constructed a localised SDG assessment framework for resource-based regions, revealing the level of regional sustainable development in Shanxi Province. Ecosystem services (ESs) benefit human society through various means, including provisioning, regulating, cultural and supporting services, and are crucial to human health and development. Regarding the classification and quantitative assessment of ESs, the

academic community has developed a variety of relatively mature and systematic models and technical tools. The development and application of tools such as the InVEST model, the ARIES (Artificial Intelligence for Ecosystem Services) model, and 3S technology have greatly facilitated the comprehensive assessment, simulation, and prediction of various ESs. Among these tools, the InVEST model demonstrates significant advantages due to its relatively low data requirements and applicability across multiple spatiotemporal scales. Furthermore, this model is capable of handling the complex interactions among ecosystem services, enabling the analysis of their geospatial distribution, visualisation, and dynamic changes. By utilising the InVEST model to assess ecological functions such as water yield (WY), carbon stock (CS), soil conservation (SC) and vegetation cover (FVC), it is possible to reveal the supportive and constraining roles of the ecological environment in urban sustainable development.

However, there remains a lack of specific quantitative analysis of the relationship between ESs and spatial variations in the Sustainable Development Goals (SDGs), and key questions regarding the relationship between ESs and the SDGs remain unanswered. Numerous methods have been employed to elucidate the complex trade-offs and synergies between ESs and the SDGs. Among these, correlation analysis and the Analytic Hierarchy Process (AHP) are frequently used to characterise trade-offs and synergies at the aggregate level; geographically weighted regression and the Coupling Coordination Degree (CCD) model further reveal the spatial heterogeneity of these relationships. Influenced by variations in natural resource endowments and socio-economic conditions, the relationship between ESs and the SDGs exhibits significant spatial heterogeneity; consequently, spatial analysis methods are better able to reflect the actual linkages between the two than non-spatial models. Although a large body of research has explored the coupling mechanisms between ecosystems and human social development using the CCD model—to some extent addressing the shortfall in early SDG research regarding the focus on ecosystem services—the relevant analytical results remain largely confined to the level of correlation and have not yet effectively revealed the causal relationship between the two.

It is therefore necessary to conduct a regression analysis of the relationship between ecosystem services (ESs) and the Sustainable Development Goals (SDGs) in order to better elucidate the specific nature of the link between the two. Multi-scale Geographically Weighted Regression (MGWR) is a local form of linear regression that can be used to model spatially varying relationships; it not only accounts for geospatial dependencies but also allows for the analysis of data across different spatial scales. Many scholars have utilised the MGWR model to investigate the spatial heterogeneity of these relationships. Against this background, this study integrates Spearman's non-parametric correlation analysis with the MGWR model to systematically explore the interactions between ESs and SDG 11 across the study area. We examine these relationships from both temporal and spatial perspectives, with a particular focus on revealing their underlying spatial heterogeneity.

This study focuses on the “Mid-Spine Belt of Beautiful China” region. Starting from the municipal scale, it constructs an SDG 11 urban sustainable development assessment framework tailored to

regional characteristics. By integrating multi-source statistical and remote sensing data, and utilising Spearman's correlation analysis and the MGWR model, the study examines the spatio-temporal patterns of association and spatial heterogeneity between ecosystem services (ESs) and urban sustainable development. Concurrently, the Self-Organising Map (SOM) neural network method is employed to integrate and cluster ESs with SDG 11 indicators, thereby constructing an "ESs–SDG 11" spatial coupling package to identify urban sustainable development patterns and key constraining factors across different regions. The findings provide a scientific basis for differentiated urban management and sustainable development policies in the "Mid-Spine Belt of Beautiful China" region, whilst also provides a theoretical framework for the spatial optimisation of sustainable development under the "Beautiful China" initiative.

2. Study Area

The proposal of the "Beautiful China Central Spine Belt" represents a systematic summary of the issue of regional development imbalances in China. The formation of this concept is closely linked to the disparities in population distribution and regional development revealed by the "Hu-Huan-Yong Line". In their research, Academician Guo Huadong and other scholars have discovered that, in recent decades, both the demographic and economic centres of gravity in China have shifted markedly. A spatial belt with distinct transitional characteristics has gradually formed in the vicinity of the Hu-Huan-Yong Line. As this belt plays a pivotal role in the national landscape by connecting the east and driving the west, it has been aptly named the "Mid-Spine Belt of Beautiful China". This region is approximately 100 to 200 kilometres wide, with its core area covering nine provinces—Heilongjiang, Jilin, Shanxi, Shaanxi, Gansu, Ningxia, Sichuan and Yunnan—as well as the three municipalities of Beijing, Tianjin and Chongqing, whilst also extending to areas such as Liaoning, Hebei and Qinghai. The entire Central Spine Belt comprises approximately 400 county-level administrative units, accounting for a quarter of the country's land area, with both natural conditions and cultural characteristics exhibiting distinct regional variations. Consequently, the "Mid-Spine Belt of Beautiful China" is divided into four regions for discussion, namely the Northeastern section (I), Middle section 1 (II-1), Middle section 2 (II-2), and Southwestern section (III). The Northeast section encompasses Heilongjiang, Liaoning, and Jilin; the Middle section 1 includes Hebei, Shanxi, and Inner Mongolia; the Middle section 2 comprises Gansu, Qinghai, Shaanxi, and Ningxia; and the Southwest section covers Yunnan, Sichuan, and Chongqing. The "Mid-Spine Belt of Beautiful China" refers to the traditional semi-agricultural and pastoral production and living areas situated to the south-east and north-west of the "Hu-Huan-Yong Line". This region boasts a rich and diverse natural ecological environment, as well as a wealth of ethnic and cultural resources. It constitutes a cluster of relatively impoverished areas in China, whilst also serving as a vital productive space and an important ecological security barrier for the country.



Figure 1. Spatial Pattern of the “Mid-Spine Belt of Beautiful China”

Source: Reproduced from Wang et al. (2021), Bulletin of the Chinese Academy of Sciences, with permission

3. Data and Methods

3.1 Data Sources and Preprocessing

The selection of datasets for this study was based on three key criteria.

(1) Spatiotemporal coverage completeness: Priority was given to datasets providing long-term continuous observation records (2015-2023), such as the “1km resolution national annual precipitation raster data (1901-2023)” and “China 1km High-Resolution High-Quality Annual PM2.5 Dataset (2000-2024)”, and “1km Resolution Monthly Potential Evapotranspiration Grid Data”.

(2) Spatial Resolution: High spatial resolution is crucial for accurately characterising the spatial distribution of environmental and socio-economic activities. For instance, selecting the “China 30-metre resolution annual land cover data (2015-2023)” and the “STRM 90-metre resolution DEM terrain dataset” enables precise capture of the spatial heterogeneity of Environmental Services (ESs) and Sustainable Development Goal11 (SDGs), particularly in topographically complex regions.

(3) Data quality: Select datasets from authoritative institutions and internationally recognised databases that undergo rigorous quality control to ensure high precision and reliability, such as the Food and Agriculture Organisation of the United Nations’ World Soil Database and the National Centre for Earth System Science Data.

During the data pre-processing stage, the statistical data was primarily sourced from the China Statistical Yearbook and the China Urban Statistical Yearbook for the years 2015, 2017, 2019, 2021 and 2023. Where data was missing, we supplemented it by referring to statistical bulletins on the socio-economic development of urban districts, and replaced some missing values with recent averages.

Using ArcGIS Pro software, we matched the statistical data to the corresponding study areas based on

the names of the 188 urban districts. Simultaneously, using the vector maps of each area as a mask, we cropped the PM_{2.5}, CO₂ and SO₂ data, calculated the annual averages for each area, and used these as specific indicators for quantifying the Sustainable Development Goals. Furthermore, we utilised global soil data from the World Soil Database and, based on the empirical estimation model proposed by Wenzuo Zhou , calculated the available water content for vegetation within the study areas. The data utilised in this research and their respective sources are detailed in Table 1.

Table 1. Data Information and Data Sources

Data	Spatial resolution	Data Source	Index
1985-2023 30-metre resolution land cover data	30×30m	https://zenodo.org/record/12779975	Land cover
1901-2023 National Annual Precipitation Grid Data at 1km Resolution	1km×1km	https://data.tpdc.ac.cn/zh-hans/data/faae7605-a0f2-4d18-b28f-5cee413766a2	Annual average precipitation
Monthly potential evapotranspiration grid data at 1 km resolution for the period 1901-2023	1km×1km	https://data.tpdc.ac.cn/zh-hans/data/8b11da09-1a40-4014-bd3d-2b86e6dcccad4	Evapotranspiration
China's 100-metre spatial resolution bedrock depth map	100m×100m	https://doi.org/10.1038/s41597-019-0345-6	Root restriction layer depth
China's 1-kilometre high-resolution, high-quality annual PM _{2.5} dataset (2000-2023)	1km×1km	https://nnu.geodata.cn/fatured_data.html#	PM _{2.5}
China's 1km High-Resolution, High-Quality Annual Near-Surface SO ₂ Dataset (2019-2023)	1km×1km	https://nnu.geodata.cn/fatured_data.html#	SO ₂

3.2 Methodology

This study integrated a variety of analytical methods to investigate the relationship between ecosystem services (ESs) within the ‘Mid-Spine Belt of Beautiful China’ and SDG 11 (Sustainable Urban

Development). Specifically, we utilised the InVEST model to quantify three core ecosystem services (WY, SC, CS) for the period 2015-2023; vegetation cover (FVC) was selected to characterise the level of urban green space in the region. For the three sub-indicators of SDG 11—economic, social and environmental—we employed a combination of the entropy weighting method and linear weighting to determine comprehensive values. Subsequently, Spearman’s non-parametric correlation analysis and the MGWR model were employed to investigate the temporal evolution of the relationship between municipal ecosystem services (ESs) and SDG 11, whilst identifying the spatial heterogeneity patterns underlying this association. Finally, a SOM neural network was applied to construct an “ESs-SDG 11” cluster, dividing the study area into four sub-regions.

3.2.1 Quantification of Sustainable Development Goal11

(1) Indicator Selection

In selecting the evaluation indicators for SDG 11, this study took the core requirements of urban sustainable development as its fundamental basis; on the one hand, it drew upon existing relevant research findings from both domestic and international sources, and on the other, it fully integrated the actual development status of the study area. The study identified three major subsystems—economic, social and environmental—within the sustainable development framework, and selected 13 evaluation indicators corresponding to 12 specific urban sustainable development targets. The formulation of each indicator aligns with the core principles of SDG 11 and the requirements of urban development. This study categorises all evaluation indicators into positive (+) and negative (-) indicators, with the former implying that higher values are preferable and the latter implying that lower values are preferable. The final selected indicators and their corresponding Sustainable Development Goal11 are presented in Table 2. The indicators in Table 2 provide a comprehensive assessment of 13 sustainable development goals by quantifying the economic, social, and environmental dimensions critical to sustainable development. For instance, regional GDP (Gross Domestic Product) reflects economic growth and social prosperity, while the proportion of cultural and heritage preservation expenditure within fiscal spending indicates cultural investment. Hospital bed capacity and PM2.5 concentration levels reflect health and environmental quality. Furthermore, the public transport stop coverage ratio within 500 metres (%) measures urban transport accessibility. All selected indicators can quantify the specific targets of urban sustainable development goals, ensuring the construction of a holistic sustainable development assessment framework.

Table 2. Quantitative Assessment Indicators of SDG11

System layer	Subsystem layer	Sustainable Development Goal11 Indicators	Indicator layer	Direction of influence
Sustainable	Sustainable	SDG11.3 Urban	Fixed Asset Investment in	+

Urban Development Assessment	Development Goals for the Economy	development and investment	Urban Construction / GDP	
			Growth rate of urban construction land	-
			Urbanisation rate	+
		SDG11.4 Cultural Public Expenditure	Expenditure on cultural and heritage preservation / Total public expenditure (%)	+
		SDG11.5 Disaster losses	Direct economic losses from natural disasters / GDP (%)	-
		SDG11.a Regional integration	High-speed rail/road density, commuter traffic flow	+
		SDG11.1 Public services	Medical resource density, educational resources, bus density	+
		SDG11.2 Accessibility of Transport	Population coverage ratio within 500 metres of bus stops (%) Public transport/rail passenger volume per capita (passenger trips)	+
	Social Sustainable Development Goals	SDG11.3 Public Participation	Percentage of towns and streets with urban and rural planning in place (%)	+
		SDG11.5 Impact on disaster-affected populations	Disaster-related deaths + affected persons per 10,000 persons	-
		SDG11.7 Development of Public Spaces	public budget expenditure	+
		SDG 11.a Urban governance and population	Proportion of urban residents	+

Environmental Sustainable Development Goals	SDG11.6 Air and solid waste pollution, urban low-carbon levels	Per capita carbon emissions Annual average PM2.5 concentration (µg/m³)	-
	SDG11.7 Accessibility of green spaces	Per capita green space area, annual mean FVC, green space coverage rate	+
	SDG 11.3 Urban land use	Impermeable area	-

(2) Standardisation

Prior to quantification, normalise the data to eliminate the effects of differing dimensions and magnitudes.

$$Y_{\theta pq} = \frac{X_{\theta pq} - \min(X_q)}{\max(X_q) - \min(X_q)} \tag{1}$$

$$Y_{\theta pq} = \frac{\max(X_q) - X_{\theta pq}}{\max(X_q) - \min(X_q)} \tag{2}$$

$X_{\theta pq}$ denotes the original value of indicator q for county in year p; represents the normalised value of $X_{\theta pq}$; and denote the minimum and maximum values of indicator across all counties over the years.

(3) Indicator Calculation

First, the entropy weighting method is employed to determine the weights of each indicator based on information entropy principles, enabling an objective and accurate evaluation of the research subject. A higher entropy value indicates a more balanced system structure, while a smaller coefficient difference results in a lower weight (w). Subsequently, the linear weighting method is used to calculate the indicator values for sustainability and its subsystems. The specific formula is as follows:

$$P_{\theta pq} = \frac{Y_{\theta pq}}{\sum_{\theta} \sum_p Y_{\theta pq}} \tag{3}$$

$$e_q = -k \sum_{\theta} \sum_p P_{\theta pq} \ln(P_{\theta pq}), \quad k = \frac{1}{\ln(m)} \tag{4}$$

$$w_q = \frac{1 - e_q}{\sum_q (1 - e_q)} \tag{5}$$

$$S_{\theta p} = \sum_q w_q \cdot Y_{\theta pq} \tag{6}$$

In the formula, denotes the proportion of indicator in city during year p; represents the entropy value of indicator q; is the weighting factor for indicator q; and signifies the sustainable development level value for city in year p.

3.2.2 Quantification of Ecosystem Services

(1) Water Yield

Water yield (WY) constitutes a vital component of forest ecosystem services. The water supply module within the InVEST model estimates annual regional water yield to evaluate the water discharge function. The formula is as follows:

$$Y(x) = \left(1 - \frac{AET(x)}{P(x)}\right) \cdot P(x) \tag{7}$$

Where: $Y(x)$ denotes the annual WY (mm) for grid cell a ; $AET(x)$ represents the actual evapotranspiration (mm) for grid cell x in year x ; $P(x)$ indicates the annual precipitation (mm) for grid cell x ; f approximates the *Budyko curve*.

(2) Soil conservation

This study assessed soil conservation services (SC), potential erosion, and actual erosion using the sediment yield ratio module within the InVEST model. SC is calculated by subtracting actual soil erosion (USLE) from potential soil erosion (RKLS). The formula is as follows:

$$RKLS_b = R_b \times K_b \times LS_b \tag{8}$$

$$ULSE_b = R_b \times K_b \times LS_b \times C_b \times P_b \tag{9}$$

Where: R_b denotes the rainfall erosion potential factor for grid cell b , K_b represents the soil erodibility factor for grid cell b , LS_b signifies the slope length factor, C_b represents the vegetation management factor for grid b , and P_b represents the soil conservation measures factor for grid b .

(3) Carbon Stock

This study employs the Carbon module within the InVEST model to quantify the spatio-temporal distribution of CS across the CUA region. CS measurement primarily relies upon four components: aboveground biomass, belowground biomass, soil, and organic matter. The formula is as follows:

$$C_{total\ x} = \sum_{y=1}^d A_{xy} \times (C_{above\ y} + C_{below\ y} + C_{soil\ y} + C_{dead\ y}) \tag{10}$$

In the formula: C_{total} denotes the total carbon stock (t) for region x ; A_{xy} represents the area (hm^2) of land use type y within region x ; $C_{above\ y}$, $C_{below\ y}$, $C_{soil\ y}$, and $C_{dead\ y}$ denote the above-ground biogenic carbon density, below-ground biogenic carbon density, soil carbon density, and dead organic matter carbon density (t/hm^2) for land use type y , respectively; d denotes the number of land use types.

(4) Vegetation Cover

Fractional Vegetation Cover (FVC) represents the proportion of the land surface covered by vegetation; it provides a clear indication of regional vegetation growth and overall ecological conditions. It is currently widely used in various fields, including the quantification of ecosystem services, land degradation monitoring and regional sustainable development. In remote sensing data processing, most studies rely on the Normalised Difference Vegetation Index (NDVI) to calculate FVC. On the one hand, the most commonly used method within the industry is the Pixel Dichotomy Model; on the other hand, this model is based on the fundamental assumption that a single remote sensing pixel is composed of a linear combination of two components—vegetation and bare soil—in proportion to their respective

shares. The specific calculation formula is as follows:

$$FVC = \frac{NDVI - NDVI_{soil}}{NDVI_{veg} - NDVI_{soil}} \tag{11}$$

Where: NDVI denotes the actual normalised difference vegetation index for pixels; represents the NDVI value for areas of completely bare soil; denotes the NDVI value for areas with complete vegetation cover.

3.2.3 Spearman’s Non-parametric Correlation Analysis

This study employs Spearman’s non-parametric correlation analysis to identify synergies and trade-offs between ecosystem services and urban sustainable development goals. This quantitative analytical method has been applied in numerous similar studies and is capable of quantifying the direction (positive or negative) and strength of the relationship between two sets of variables. Under the criteria established in this study, a positive correlation coefficient between ESs and SDG 11, provided it meets the significance threshold, indicates a synergistic relationship; conversely, a negative correlation coefficient, when the test results are significant, is defined as a trade-off relationship.

3.2.4 Multi-Scale Geographically Weighted Regression Model

MGWR is an extended model optimised from the traditional Geographically Weighted Regression (GWR). It is capable of identifying the spatial scales at which individual independent variables influence the dependent variable, thereby effectively enhancing the reliability of the model results; it also allows various geographical processes to be analysed using the optimal bandwidth best suited to each. In this study, the MGWR model was employed to examine whether the relationship between ESs and urban Sustainable Development Goal 11 (SDG 11) exhibits spatial heterogeneity. By accounting for the spatial heterogeneity arising from multiple scales, this model provides a more reasonable explanation for the spatial variations observed in the synergistic and trade-off relationships between ESs and SDG 11. The corresponding core calculation formulae are listed below:

$$y_i = \sum_{j=0}^m \beta_{bwj}(\mu_i, \nu_i) x_{ij} + \varepsilon_i \tag{12}$$

In the equation, denotes the dependent variable for the i-th element, represents the attribute value of variable j at position i, signifies the bandwidth employed for the regression coefficient of variable j, denotes the spatial coordinates of the i-th element, and denotes the residual.

$$\hat{\varepsilon} = y - \sum_{j=1}^k \hat{f}_j \tag{13}$$

MGWR commences calculations using GWR as the initial state, initialising residuals ε_i , then iteratively determines the optimal bandwidth. In equation (13), initial residuals ε_i , additive terms \hat{f}_j , and independent variables undergo GWR weighting at $i = 1, \dots, n$ to identify optimal values, subsequently iterating until all variables k are traversed. Finally, the loop is repeated until the estimation converges to the convergence criterion.

3.2.5 Self-Organising Maps

The Self-Organising Maps (SOM) neural network, proposed by Finnish expert Professor Kohonen, is a competitive unsupervised learning neural network. It possesses strong self-learning capabilities and

excellent topological relationship preservation properties, making it highly advantageous for visualisation. The network structure primarily consists of an input layer and an output layer. The input layer receives high-dimensional data and, through a competitive learning mechanism, transforms it into two-dimensional visual outputs. Compared to traditional methods, it exhibits superior visual representativeness, robustness, nonlinear mapping capabilities, and self-learning capacity. This study employs 188 urban districts within the “Mid-Spine Belt of Beautiful China” as statistical units, conducting spatial clustering analysis based on four ESs and three types of sustainable development goals.

4. Conclusion and Analysis

4.1 Spatiotemporal Variations of ESs and Sustainable Development Goal11

4.1.1 Sustainable Development Goal11

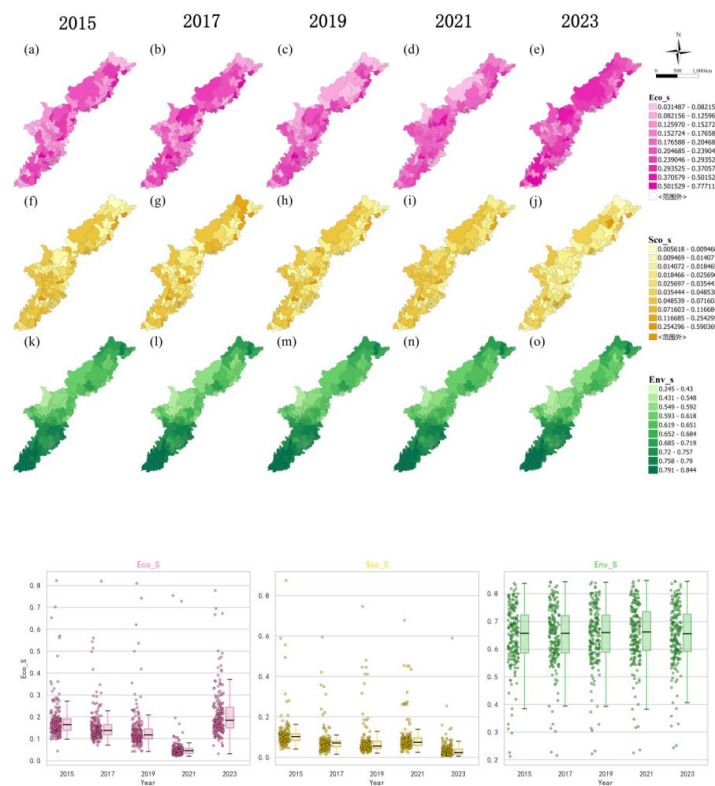


Figure 2. Spatiotemporal Patterns of 188 Municipal Sustainable Development Goal11

Note. (a-e), (f-j), and (k-o) respectively represent the spatial distribution patterns of Eco_S, Soc_S, and Env_S. (p), (q), and (r) respectively indicate the temporal trends of Eco_S, Soc_S, and Env_S

The results of this study indicate that between 2015 and 2023, the “Mid-Spine Belt of Beautiful China” exhibited significant spatial heterogeneity in terms of economic (Eco_S), social (Soc_S) and ecological (Env_S) sustainable development, with the region’s overall level of sustainable development showing a certain degree of improvement compared to 2015. The temporal trends of these three indicators were

broadly consistent, with all reaching their lowest values for the study period in 2021 and showing a marked recovery by 2023.

Overall, Eco_S exhibits a spatial pattern characterised by “high values in the Northeast and Southwest, and low values in the central region”. Old industrial cities in the Northeast, such as Shenyang, Changchun and Harbin, alongside central cities in the Southwest such as Chongqing, Chengdu and Kunming, have formed high-value economic zones driven by industrial optimisation and regional growth poles. Xi’an in the central region stands out in terms of economic performance, whilst cities in the Northwest such as Lanzhou and Yinchuan have long remained in a state of low economic value, forming distinct economic troughs.

The overall development level of Soc_S is relatively low, with stable high-value zones forming in the Northeast and Southwest. Cities such as Chongqing, Chengdu and Shenyang possess strong social service capabilities, whilst social development in the central and north-western regions lags behind. Xi’an, with its high-quality educational and medical resources, has exerted a positive driving effect on surrounding areas, and the coverage of high-value zones for social development has continued to expand between 2019 and 2023.

Spatial disparities are most pronounced in Env_S, which exhibits a pattern of ‘high at the periphery, low in the centre’. Ecological barrier zones such as eastern Qinghai, the western Sichuan Plateau and the central Yunnan hills have long maintained high ecological standards, whilst the Guanzhong Basin and some industrial cities in the northeast suffer from relatively low ecological quality due to urban expansion and industrial agglomeration. Overall ecological quality is in a state of continuous improvement, with the extent of high-value ecological zones expanding significantly since 2019.

Overall, over the nine-year period, the three major development dimensions of the “Mid-Spine Belt of Beautiful China” exhibited significant spatial differentiation, with a generally positive trend over time. A sustainable development framework driven by dual cores in the northeast and southwest has taken shape. The central section serves as a transitional zone for coordinated socio-economic development, whilst the second central section, centred on Xi’an, is gradually realising its development potential, albeit under considerable ecological pressure.

4.1.2 Ecological Service System

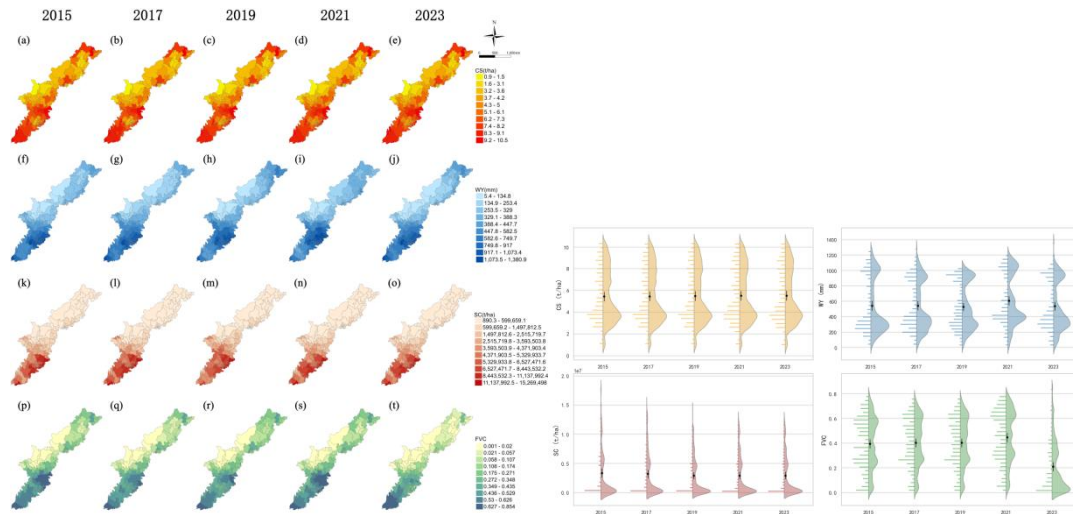


Figure 3. Spatial Patterns and Spatiotemporal Trends of Functional ESs across 188 Counties

Note. (a-e), (f-j), (k-o), (p-t) denote HQ, WY, CS, and SC, respectively; u, v, w, x denote the temporal variation trends for CS, WY, SC, and FVC, respectively Acknowledgement.

The findings indicate that the four types of ecosystem services (WY, SC, CS, FVC) across 188 cities within the “Mid-Spine Belt of Beautiful China” exhibited significant spatial heterogeneity between 2015 and 2023, with these changes being jointly influenced by topography, climatic gradients, and the natural conditions of the four major sub-regions: the north-eastern, central first, central second, and south-western sections.

FVC demonstrated sustained improvement, forming a high-value pattern along mountain ranges and green corridors. The northeastern mountainous regions, Qinling-Qilian-Three Rivers Source Belt, and Sichuan-Yunnan mountains maintained persistently high values, whereas plains cities such as Lanzhou, Yinchuan, and Xi’an urban centres exhibited relatively low FVC, with surrounding mountainous areas significantly exceeding urban core zones.

The spatial pattern of CS remains stable, with a pronounced “high in mountains—low in cities” characteristic. Changbai Mountain, Qilian Mountains, Qinling Mountains, and the Sichuan-Yunnan Plateau form stable high-value belts, while the Beijing-Tianjin-Hebei Plain, Hohhot-Baotou-Ordos City Cluster, Weihe Plain, and Chengdu-Chongqing main urban areas constitute low-value zones. Xi'an exhibits a typical basin structure with “low in the centre—high in the periphery”.

WY exhibits a “southeast high-northwest low” pattern, having rebounded after reaching a trough in 2019. High-value zones are found in the southwestern mountains and eastern northeast, while low-value zones are in the Hexi Corridor, northern Ningxia, and western Inner Mongolia. The Guanzhong Plain (including Xi’an) is a medium-to-low value zone with a slight decline.

SC exhibited an overall pattern of initial decline followed by recovery, closely linked to topography and human activity intensity. Mountainous areas maintained high values due to robust vegetation cover and minimal human disturbance, while plains and urbanised core zones (e.g., Xi’an urban area,

Chengdu-Chongqing Plain) were low-value regions. Most areas gradually recovered post-2019 following ecological engineering initiatives.

The overall trend in ESs along the Mid-Spine Belt is characterised by: steady increases in FVC and CS, indicating sustained ecological foundation enhancement; WY being significantly affected by climatic fluctuations; SC initially declining then rising, reflecting gradually evident ecological governance outcomes, though plains and urban areas remain vulnerable zones.

4.2 Spatiotemporal Relationship between ESs and SDG 11

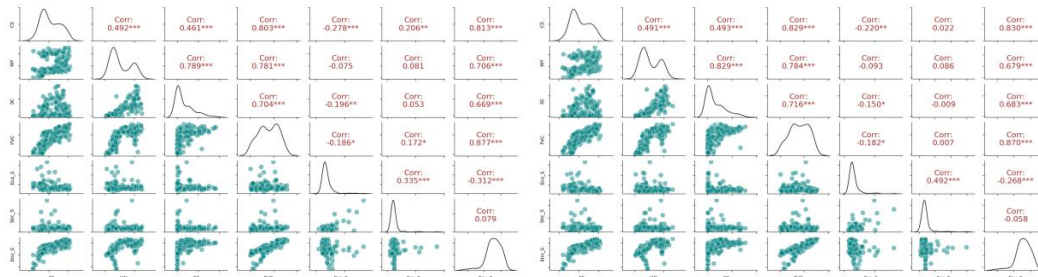
4.2.1 Correlation Analysis

A total of 60 correlations were identified between the four ecosystem services (CS, WY, SC, FVC) and the three dimensions of sustainable development (Eco_S, Soc_S, Env_S), with 20 correlations being statistically significant ($p < 0.05$). Overall, ecosystem services exhibited the most pronounced synergistic effects with Env_S and the most significant trade-offs with Eco_S.

Env_S exhibited the greatest propensity for synergistic formation. All ecosystem services maintained stable long-term positive correlations with Env_S, with CS-Env_S displaying the strongest synergy, followed by FVC-Env_S and SC-Env_S. This indicates ecosystem services provide core support for environmental sustainability. Eco_S exhibited pronounced trade-offs in the early years, though these gradually diminished. In 2015, CS, SC, and FVC all showed significant negative correlations with Eco_S, reflecting economic development's depletion of ecosystem services. However, post-2019 trade-offs weakened, indicating that green development and ecological compensation policies began improving the ecological-economic relationship. Synergy with Soc_S emerged latest. For most years, correlations between ESs and Soc_S were insignificant. Only in 2023 did WY and FVC exhibit notable synergy with Soc_S, indicating a lag in the manifestation of social benefits.

4.2.2. Spatial Heterogeneity of ESs-SDG11

2015 2017



2019 2021

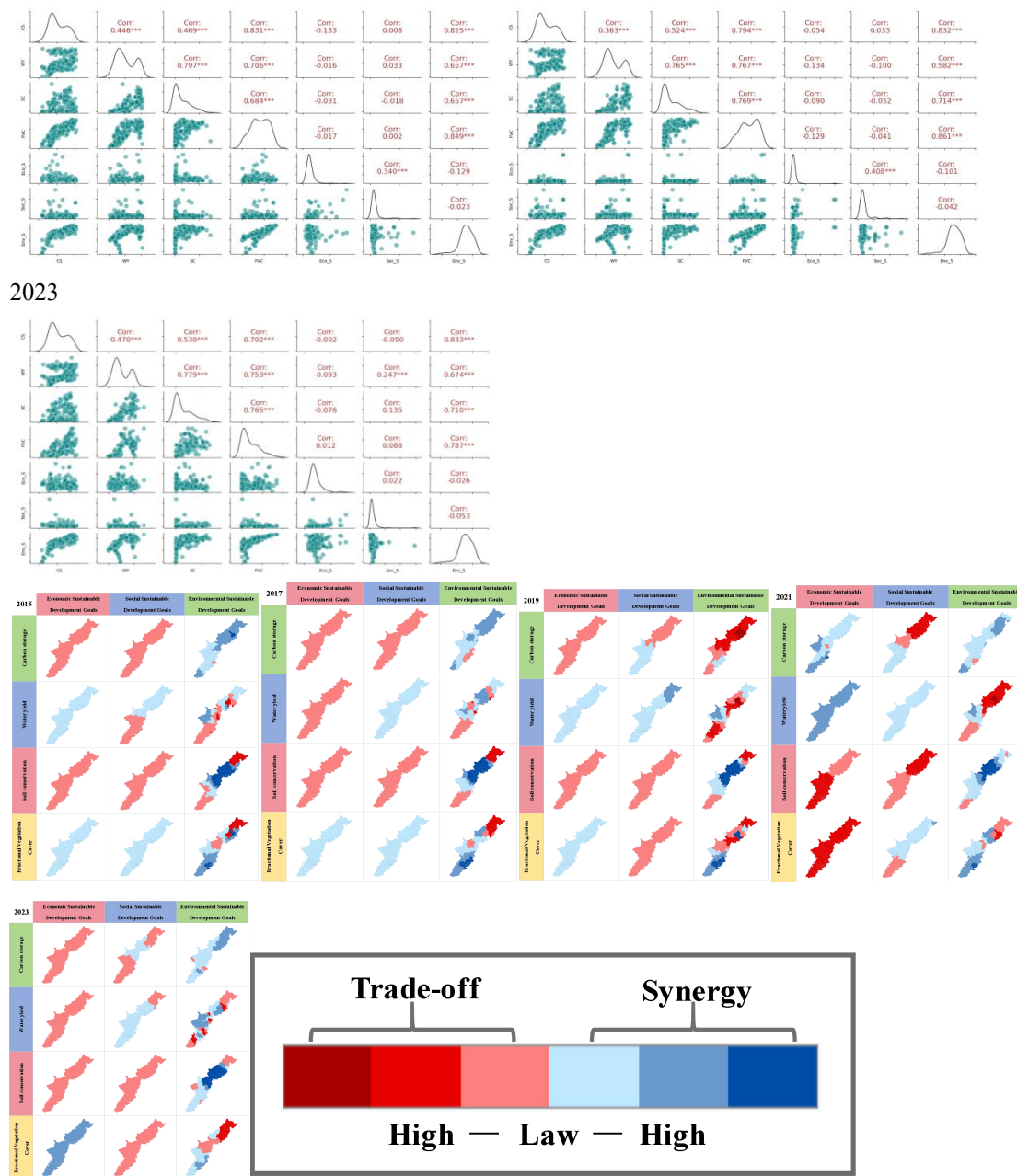


Figure 4. Correlation Coefficients between ESs and SDGs, Spatial Synergistic Effects, and Trade-off Matrix

MGWR results reveal significant spatial heterogeneity between ESs and the three dimensions of SDG11. Overall, CS, WY, SC and NDVI generally exhibit high synergy with Env_S, indicating that ecosystem services most consistently promote environmental sustainability. while CS-Eco_S, SC-Eco_S, and some WY-Soc_S still exhibit local trade-offs, reflecting persistent tensions between ecological provisioning and socio-economic development.

Spatially, The Northeastern section (Heilongjiang, Jilin, Liaoning): Forested areas show strongest CS-Env_S and NDVI-Env_S synergies, constituting typical environmental support zones; while minor

trade-offs exist between WY-Eco_S in some plains areas. The Middle section 1(Hebei,Shanxi,Inner Mongolia): ESs-SDG11 differentiation is pronounced. Ecological-economic coordination is relatively good in mountainous counties, whereas trade-offs emerge in energy-intensive regions; WY-Soc_S and NDVI-Soc_S synergies strengthen near the Beijing metropolitan area and Taiyuan urban agglomeration. The Middle section 2 (Gansu, Ningxia, Qinghai, Shaanxi): Exhibits a coexisting pattern of “ecological synergy zones - resource constraint zones - urban expansion pressure belts”. Water resource limitations in semi-arid areas cause WY-Eco_S trade-offs, while SC-Env_S and CS-Env_S synergies are pronounced in the Qinghai-Gansu-Longxi ecological barrier zone. The Xi’an metropolitan area displays typical composite characteristics of “coexisting ecological-economic trade-offs and socio-environmental synergies”. Southwestern section (Sichuan-Chongqing-Yunnan): Mountainous regions exhibit strongest ecological synergy (concentrated high CS/SC/NDVI-Env_S values), while local trade-offs between economic and social dimensions occur in parts of the Chengdu-Chongqing metropolitan area.

From a temporal perspective, the high-synergy zones for ESs-SDG11 expanded along the central mountain ridge from northeast to southwest between 2015 and 2023, demonstrating enhanced overall continuity. Environmental dimension synergy proved most stable, economic dimension fluctuations were most pronounced, while social dimension synergy significantly improved in later years, indicating regional sustainable development is progressing towards “enhanced synergy”.

5. Discussion

5.1 Gradient Effects and SDG11 Variations

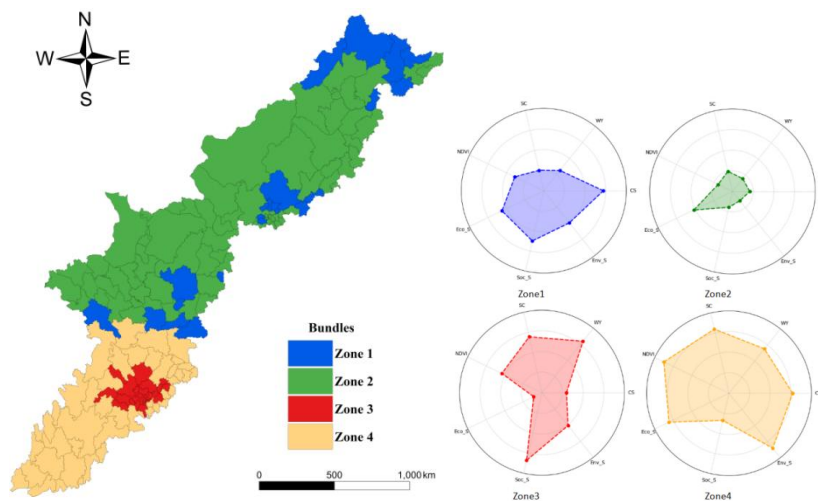


Figure 5. “ESs-SDG11” Bundles and the Spatial Patterns

Drawing on 2023 ESs and SDG 11 data for the “Mid-Spine Belt of Beautiful China”, this study constructs an “ESs-SDG11” bundle. Using a SOM neural network, four ESs-SDG 11 clusters were identified at the city level, dividing the study area into four sub-regions. The results indicate that

topographic gradients have a significant impact on the achievement of SDG 11 across regions, with distinct spatial differentiation emerging in urban sustainable development within the “Mid-Spine Belt of Beautiful China” (Figure 5). The four sub-regions exhibit distinct characteristics in terms of ESs and socio-economic development. Zone 1 possesses superior ecological foundations, with socio-economic development at a moderate level and balanced proportions across various indicators, representing a region of stable development. Zone 2 possesses abundant ecological resources but exhibits relatively weak economic growth and supporting services; constrained by its location and resources, it is characterised by strong ecological conditions but lagging development. Zone 3 has the most favourable economic and social development indicators, but its ES values—such as carbon storage, vegetation cover and soil and water conservation—are relatively low; the advancement of urbanisation has imposed a heavy ecological burden, necessitating a focus on preventing the risk of ecological overload. Zone 4 exhibits high levels across ecological, economic, and social dimensions, representing the optimal sustainable development model for cities in the central mountain belt. A clear developmental gradient emerges: ecologically dominant (Zone 2)→balanced (Zone 1)→ synergistic (Zone 4) → stressed (Zone 3).

5.2 Impact of Natural and Economic Development on Ecosystem Services

Affected by complex terrain conditions and regional differences in natural endowments, the municipal ecosystem services (ESs) in the “Mid-Spine Belt of Beautiful China” show significant spatial differentiation, generally presenting a gradient distribution pattern of medium in the northeast, lower in the central region, and higher in the southwest. These spatial differences are closely related to terrain undulation, ecological foundations, and the intensity of human activities. Among them, the Northeastern section is rich in forest and wetland resources, with a complete ecological structure, and its ecological environment and social-supporting ecosystem service functions are particularly prominent; whereas the Middle section 1 and Middle section 2 feature highly fragmented terrain and rapid urbanization, with intensified human ecological disturbances, resulting in a significant decline in the overall ESs supply capacity of the area.

This distribution pattern largely aligns with previous observations in China’s mountainous and agro-pastoral transition zones. In the Middle section 1 (Hebei, Shanxi, Inner Mongolia) and parts of the Middle section 2 (Gansu, Ningxia, Shaanxi), population concentration, industrial development, and infrastructure expansion have driven rapid increases in natural resource demand, resulting in pronounced land-use changes and ecological disturbances. In certain areas, urban expansion, energy extraction, and transport infrastructure development have substantially increased ecological risks such as vegetation fragmentation, soil erosion, and water quality pressures, threatening regional ES provisioning capacity .

In contrast, the Southwest section has complex terrain and limited development and construction, with relatively low overall intensity of human disturbances. The integrity of natural ecosystems is well maintained, and key ecosystem services such as water conservation, soil retention, and habitat quality

remain at high levels. However, special regions such as the Hengduan Mountains, Wumeng Mountains, and Daliang Mountains are highly sensitive to terrain and climate, and overall, ecosystem services exhibit strong spatiotemporal vulnerability characteristics.

The SOM clustering results further indicate that the ESs fluctuation characteristics in Zone II are significant, and the urban ecological service levels in areas with high terrain gradients are obviously lower than those in other regions at the same latitude, mainly due to the combined effects of regional climate aridification, uneven precipitation distribution, and human disturbances. From 2014 to 2018, the water deficit in this region intensified, and the ecological degradation trend was evident, which is consistent with research conclusions related to climate change in arid areas.

Overall, the spatial variations in ecosystem services (ESs) across the ‘Mid-Spine Belt of Beautiful China’ are the result of constraints imposed by both natural conditions and socio-economic development. The combined effects of the natural environment and human activities have shaped a gradient distribution pattern extending from the north-east to the centre and south-west, and have also caused the spatial evolution of ESs to exhibit characteristics where natural endowments, economic development and ecological pressures are mutually interlinked.

5.3 Trade-offs and Synergies between ESs and SDG11

The “Mid-Spine Belt of Beautiful China” links the Northeast, Middle 1, Middle 2 and the Southwest; these regions exhibit significant differences in terms of natural conditions, economic foundations and the pace of urbanisation, resulting in distinct trade-offs and synergies between ESs and SDG 11 across different areas. Whilst the Northeast and Southwest regions are predominantly characterised by synergistic relationships, Middle 1 and Middle 2 are notably defined by trade-off relationships, clearly illustrating the spatial imbalance between development pressures and ecological carrying capacity across these regions.

The Northeast section (Heilongjiang, Jilin, Liaoning) boasts abundant forest resources and a well-preserved ecosystem, with generally high SC, NDVI and Env_S values, whilst the intensity of human development in the region is relatively low. Combined with the results of SOM clustering, it can be seen that local ecosystem services (ESs) and SDG 11 are largely positively correlated, demonstrating a strong synergy. These superior ecological conditions have stabilised multiple development indicators, such as liveability and green space accessibility, making this the section of the Central Spine where ecology and urban development are best aligned.

In contrast, the Middle section 1 (Hebei, Shanxi) is home to a large number of resource-based cities and areas where agricultural and pastoral lands intersect. The economy is heavily weighted towards mineral extraction, heavy industry and energy development, and urban expansion is proceeding at a rapid pace. High-intensity land development has fragmented the native ecosystem and continuously increased environmental pressures; the region’s SC, Env_S and SDG 11 indicators related to liveability and green development often exhibit trade-offs. The urbanisation of resource-based cities is eroding ecological reserves, hindering the implementation of sustainable development.

Based on the SOM classification results, the inter-annual fluctuations in ESs in the Middle section 2 (Gansu, Qinghai, Ningxia, and parts of Shaanxi) are the most pronounced among the four sub-regions. The region's arid climate and uneven rainfall distribution, coupled with increasing human disturbance, render the ecological environment highly sensitive to climate change. In many counties, soil and water conservation and water conservation capacities are relatively weak, creating trade-offs with development indicators such as liveable environments and urban resilience. Extreme weather further exacerbates ecological pressures; therefore, future progress on SDG 11 requires a coordinated approach to ecological restoration and urban safety development.

The Southwestern section features predominantly mountainous terrain with steep slopes, where large-scale development is constrained by topography. Leveraging superior vegetation and biological resources, the overall level of ecosystem services (ESs) ranks among the highest. The excellent ecological foundation has supported SDG 11 initiatives such as cultural and tourism carrying capacity, green transport and urban green spaces, with the region as a whole characterised by coordinated development. However, some mountainous counties and cities are currently undergoing a period of rapid development, and in certain urban areas, economic expansion has been accompanied by ecological degradation, creating localised trade-offs.

In summary, the 'Mid-Spine Belt of Beautiful China' ESs and SDG 11 exhibit both synergistic and trade-off relationships; the level of synergy is determined by the ecological foundation, whilst pressures arising from economic development tend to give rise to trade-offs. The Northeast and Southwest regions, with their superior ecological conditions and relatively low levels of population development, are more likely to exhibit synergy between the two indicators; whereas in the Middle section 1 and 2, where resource extraction and urban expansion are prevalent, trade-off conflicts are more pronounced. To steadily improve regional ESs and SDG 11 levels, it is necessary to simultaneously implement ecological conservation, industrial upgrading and green urban development, thereby ensuring the steady realisation of sustainable regional development.

5.4 Sustainable Development Pathways for SDG11

Since the adoption of SDG 11, how to coordinate social and ecological planning at the regional level has been a key focus of discussion among researchers and policymakers. Drawing on the results of four sub-regions identified through SOM clustering, this paper proposes differentiated development strategies for the 'Mid-Spine Belt of Beautiful China' in line with SDG 11, with a view to reconciling the conflict between ecosystem services (ESs) and sustainable urban development across different localities.

Zone 1 covers the mountainous forest areas of Heilongjiang, Jilin and Liaoning, where ES indicators such as SC, NDVI and Env_S are generally excellent. The region should revitalise existing ecological resources by, on the one hand, continuing to implement forest management and ecological restoration whilst improving the development of nature reserves; and on the other hand, leveraging the high-quality ecological environment to develop health and wellness tourism and eco-tourism, thereby

increasing income whilst safeguarding biodiversity.

Zone 2 encompasses development zones surrounding Beijing, including parts of Shanxi, Hebei and central-eastern Inner Mongolia. Urbanisation is advancing rapidly and urban construction land is expanding continuously, yet overall ES values remain relatively weak. Building upon the consolidation of existing infrastructure and ensuring compliance with SDG 11 standards, the region must guard against potential ecological deficits. Control the unregulated expansion of towns and cities, accelerate the regeneration of existing urban areas, and increase the allocation of ecological land within urban centres. Utilise ecological compensation mechanisms to mitigate the impact of urban development on surrounding pristine ecosystems.

Zone 3 is situated on the Loess Plateau and in the arid north-western regions, where the natural ecological environment is inherently fragile and climate change can easily affect various ecological indicators. The primary task for development is to stabilise the livelihoods and economic benefits of the population, improve farming and livestock-rearing practices, and enhance the efficiency of water, soil and food utilisation. Simultaneously implement soil and water conservation and desertification control projects to fortify regional ecological barriers and enhance the disaster resilience of both communities and ecosystems.

Zone 4 constitutes the mountainous transition zone between Sichuan, Chongqing and Yunnan, boasting high-level ecosystem services whilst facing development pressures from urban expansion. Local authorities must accelerate the green transformation of traditional industries, convert ecological advantages into industrial benefits, cultivate complete ecological industrial chains, and achieve mutual gains for both the environment and the economy. By relying on planning constraints and supporting policies, we can avoid further ecological damage caused by extensive development and balance environmental benefits with economic returns; this approach also aligns with the macro-level national orientation towards integrated urban-rural development and regional coordination.

In summary, each sub-region of the ‘Mid-Spine Belt of Beautiful China’ must build upon its own ecological endowments and current development status to implement appropriate management and control measures, thereby gradually achieving synergistic progress in both ESs and SDG 11.

5.5 Uncertainty Analysis

This study selected four core indicators—CS, WY, SC and FVC—to quantify ecosystem services. By combining these with various statistical data, a city-level evaluation framework for SDG 11 was established; however, some uncertainties remain regarding model configuration and parameter selection.

Firstly, the parameters used to estimate ecosystem services (ESs) were derived from existing literature, and the specific parameter values may still slightly affect the simulation results. Nevertheless, the practicality of this set of indicators and the model has been validated by numerous existing studies, and the spatial patterns of ESs derived from this research are generally reliable.

Secondly, the “Mid-Spine Belt of Beautiful China” region features a complex array of landforms and

significant regional variations in natural environments. The raw ES data, derived from high-resolution remote sensing, was aggregated at the municipal level for analysis in this study. This spatial aggregation may obscure subtle ecological differences within small areas; nevertheless, the overall spatial patterns are largely consistent with previous research findings. Future studies could employ refined downscaling methods to mitigate such errors.

Furthermore, this study selected only indicators relevant to SDG 11; future research could be expanded to cover all 17 SDGs, utilising a more comprehensive set of indicators to explore the interrelationships between ecosystem services and sustainable development in greater depth.

6. Conclusions

This study takes the “Mid-Spine Belt of Beautiful China”—spanning the Northeast, North, Northwest and Southwest regions—as its research area. It constructs an ESs–SDG11 coupled indicator system and systematically analyses the spatio-temporal patterns and interactions between regional ecosystem services and SDG11 from 2015 to 2023. Furthermore, regional typology classification was carried out using a SOM neural network, yielding the following main conclusions: (1) During the study period, the level of SDG 11 in the “Mid-Spine Belt of Beautiful China” generally showed a fluctuating upward trend, although disparities in municipal development remained significant. The north-eastern and south-western sub-regions performed better, whilst the SDG11 levels in resource-based and energy-based counties were generally low. (2) Topographical undulation significantly influences regional development: Eco_S and Soc_S decrease with increasing elevation, whereas Env_S increases simultaneously, forming a gradient characterised by inverse changes between socio-economic and ecological-environmental conditions. Improving public services, transport, and healthcare and educational resources can effectively enhance urban liveability and development resilience. (3) The spatial heterogeneity of ESs within the study area is particularly pronounced. The decline in the middle and upper reaches of the north-western arid region is most pronounced, with SC and WY remaining at low levels in some areas over the long term. It is necessary to enhance regional ecological carrying capacity through water resource management, desertification control and ecological restoration. (4) The trade-off and synergy between ecosystem services and SDG 11 exhibit distinct spatial differentiation: the north-eastern and south-western segments are characterised by synergistic effects, whilst the transition zones in North China and the Northwest exhibit more pronounced trade-off conflicts. Urban expansion and resource development deplete ecosystem services, constraining the steady advancement of SDG 11; a green transition is the core pathway for reconciling these two aspects. (5) Based on SOM clustering, this study identifies four sub-regions and proposes targeted sustainable development strategies. These strategies can facilitate regional industrial transformation, the development of the ecological services sector, and urban-rural integration whilst safeguarding ecological security, thereby providing a scientific reference for the “coordinated, high-quality development” of the “Mid-Spine Belt of Beautiful China”.

Overall, clarifying the mechanisms through which ecosystem services and SDG 11 interact across different regions can effectively contribute to the enhancement of ecological well-being and the construction and development of sustainable cities.

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