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Dynamic Simulation and Tradeoffs and Synergies of Ecosystem Service Value in Metropolitan Suburbs Using the PLUS Model

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Abstract

INTRODUCTION: Due to rapid economic development and continuous human activities, land use changes in the suburbs of metropolitan areas are drastic, which in turn affects the balance of ecosystem functions. Analyzing and predicting the ecological service value characteristics and trade-offs in rapidly urbanizing regions is of great significance for promoting high-quality regional development.
AIM: This study attempts to reveal the trade-off and synergistic characteristics between the internal values of ecosystem services in suburban metropolitan areas under the influence of rapid urbanization.
METHODS: Based on the patch-generating land use simulation (PLUS) model, simulated the land use changes in Xinzheng City under multiple scenarios in 2030, combined with methods such as equivalent factor method and spatial autocorrelation analysis， estimating, and predicting the ecosystem service value and its trade-off synergy relationship in Xinzheng City from 1980 to 2030.
RESULTS: The value of ecosystem services in Xinzheng City continues to decline, hydrological regulation and soil conservation are the most important ecosystem service functions, under the scenario of farmland protection, ESV shows a stable growth trend. The synergistic relationship between various functions of ESV is significant, the Shizu Mountain National Forest Park, Shuangji River and other high agglomeration areas, as well as the Airport Economic Zone and Nanlonghu Town and other low agglomeration areas, all show a synergistic relationship, with only a portion of the southern side of the main urban area of Xinzheng showing a balancing relationship.
CONCLUSIONS: Our findings can scientifically identify the environmental advantages of ecological sustainable development in Xinzheng City, and transform them into development advantages, providing provide strong technical support for the spatial ecological restoration and ecological security pattern construction of metropolitan suburbs.

Keywords: Ecosystem service value; Tradeoffs and synergies; PLUS simulation; Metropolitan suburb

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1. Introduction

The benefits that humans derive from ecosystems are referred to as ecosystem service value (ESV), which contribute to the maintenance of social and economic development through various ecosystem elements, functions, and structures [1]. The Millennium Ecosystem Assessment, conducted by the United Nations in 2001, underscored that approximately 60% of global ecosystems have undergone or are undergoing degradation due to ongoing human activities [2]. Among them, territorial spatial development serves as a significant manifestation of human activities in ecosystems, and the alterations in its structure and functions have far-reaching consequences, profoundly influencing the formation, supply, and distribution of regional ecosystem service functions. Consequently, a mutually restricted and enhanced relationship emerges between territorial spatial evolution and

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ecosystem service functions [3-4]. Given China's ever-evolving urban landscapes, human construction and development-related actions have brought about changes in spatial structures and regional functions of urban spaces, potentially endangering regional ecological benefits and environmental sustainability [5]. Notably, amid the rapid urbanization process, metropolitan suburbs stand out as areas characterized by the most severe land use and pronounced contradiction between human demands and land resources. Therefore, gaining a comprehensive understanding of the evolutionary trajectory and the mechanisms impacting ESV in these regions holds vital practical implications for the formulation of scientific and rational control policies, as well as strategies for the ecological restoration of land [6-7].

At present, researchers at home and abroad have made significant progress in understanding the value of ecosystem services. A significant body of related research builds upon the ecosystem value framework established by Xie et al. [8]. Methodologies such as mathematical statistics [9] and geographic information system (GIS) spatial analysis [10] have been employed to study the spatiotemporal evolution and driving mechanisms of regional ESV. These studies have primarily focused on understanding the ecological value responses resulting from changes in territorial spatial patterns during specific time frames. In recent years, researchers have ventured into utilizing multi-scenario simulations to reveal the influence mechanism of future territorial spatial evolution on ESV [11-12]. However, there remains a need for a comprehensive understanding of the complex tradeoffs and synergies among diverse ecological functions within future multi-scenario contexts. Addressing these gaps, this study employs a multi-scenario simulation of national land space and combines it with the spatial autocorrelation analysis method to analyze the tradeoffs and synergies among ecosystem functions within the empirical region.

First, by employing the theoretical framework comprising ESV assessment and the principles of tradeoff and synergy theory, the present study explores the characteristics of land use change in Xinzheng City from 1980 to 2020 and estimates ESV by utilizing the ESV equivalent estimation method. Second, the patterns governing changes in land use in Xinzheng City during 1980–2020 are identified, and the ESV for the year 2030 is simulated under various scenarios, namely, natural development, urban development, cultivated land protection, and ecological protection. The simulations are conducted employing the Patch-generating Land Use Simulation (PLUS) model, coupled with multi-period high-precision land use data. Finally, the study culminates by analyzing the tradeoff and synergic relationships inherent within the ESV framework of Xinzheng City. This analysis utilizes the spatial autocorrelation method, which effectively coordinates the spatial contradiction between rapid urban development and ecological protection and holds substantial implications for optimizing the territorial spatial patterns and ensuring the ecological safety of territorial space.

The main contributions of this research are: First, it establishes a comprehensive research framework focused on the characteristics and mechanisms of spatiotemporal evolutions in ESV within metropolitan suburbs in a context of rapid urbanization. This framework considerably enriches the theoretical understanding of ESV in metropolitan suburbs. Second, employing Xinzheng City as the research object, the study conducts simulations of production–living–ecological (PLE) land use changes across diverse scenarios for the year 2030, and corresponding assessments of ESV are conducted using the PLUS model. Building on this foundation, the analysis delves into the tradeoff and synergic relationships, which can be used to scientifically identify the types of land use under the key protection for maintaining ecological sustainable development. By converting Xinzheng City's resource and environmental advantages into developmental advantages, this research offers both theoretical and practical guidance for effectively shaping an ecologically sustainable development pattern that prioritizes territorial safety.

2. Review and comments on references

In the realm of ESV research, numerous domestic and international researchers have amassed abundant research results. Daily (1997) notably explored the foundational concept of ecosystem services in his book and developed the quantitative indices of ecosystem services in monetary units [13]. Furthermore, Costanza et al. (1997) formulated a table of global ecosystem service equivalence factors that set the stage for subsequent studies [14]. Building upon these developments, domestic researchers such as Xie et al. (2003; 2015) developed the "Table of Equivalents of Ecosystem Service Values Supplied by Per Unit Area of Terrestrial Ecosystem in China," which has gained wide acceptance and application among domestic scholars for ESV assessments [15-16]. These research endeavors have primarily focused on diverse aspects, including theory and system construction [17], change law [18-19], spatiotemporal evolution [20-21], simulation [22-23], type characteristics [24], and influencing factors [25].

In the evolving landscape of research, some scholars analyzed the implications of future land use type changes on ESV across diverse scenarios and further developed more effective and scientific sustainable development measures. For instance, Campos et al. (2020) investigated the effects of changing land use on ESV within the prospective agroforestry space under varying scenarios and developed a novel concept of ecosystem service sustainability index [26]. Zhou et al. (2021) simulated the land use changes in Zhaoyuan City in 2035 under the baseline scenario, the abandoned mining area restoration scenario, and the urban and rural construction land consolidation scenario using the Markov–Future Land Use Simulation (FLUS) model [27]. Furthermore, Zhang et al. (2022) estimated ESV across different future shared socioeconomic pathway-representative concentration pathway (SSP-RCP) scenarios for China and explored the characteristics underpinning spatiotemporal evolutions in ecosystem services in China [28]. At present, a majority of relevant findings stem from simulations established on divergent scenarios grounded in the current development trend and the actual conditions of the research area. However, few studies have addressed dynamic predictions and the intricate relationships governing these changes, especially the intricate change laws and the tradeoff and synergic relationships of ESV in future contexts.

In recent years, many domestic and international researchers have analyzed tradeoffs among diverse ecosystems in various regions using methods such as correlation analysis and constraint line analysis in ecosystem services research. Dong et al. (2019) examined the ecological impacts of Taibai Lake in Hubei Province through correlation analysis. This analysis unveiled the coordination pattern among various ecosystem services [29]. Zeng et al. (2019) employed the root-mean-square deviation method to elucidate tradeoffs and synergies within the ESV of secondary forests in different spatiotemporal evolutions [30]. Wu et al. (2022) assessed the features of spatiotemporal changes and tradeoffs in the ESV in forestry-dominated counties. This evaluation utilized the corrected ESV estimation model and correlation analysis method, aiming to analyze the correlation between ESV and human activity intensity [31]. While these methods boast advantages in terms of their simplicity and operability and demonstrate certain guiding significance for the sustainable ecosystem development, quantifying the relationships among different ESVs can be challenging, rendering their results relatively unstable. Moreover, traditional tradeoff approaches for ecosystem services lack the capacity to effectively demonstrate disparities between current and optimal ESV allocations. Thus, these methods exhibit difficulty in providing more scientific insights to enhance ecosystem service tradeoffs.

Within the realm of spatial land use simulation research, existing ecosystem service simulation models such as Cellular Automaton (CA)–Markov [32], FLUS [33-34], and Conversion of Land Use and its Effects at Small Regional Extent (CLUE-S) [35-36] exhibit certain limitations. These models often fail to effectively elucidate the inducements of changes in various land use types and reveal patch-level changes across multiple land use types. Notably, the PLUS model has been improved based on the abovementioned models. As a result, it offers more accurate and reliable simulation results of transformation law concerning land use. However, the integration of PLUS with ecosystem service models to predict changes in ecosystem service functions and to analyze the tradeoffs and synergies among these functions remains limited to only a few future land use simulation studies.

In summary, the study of ESV offers several avenues for further exploration. Most researchers have examined the impact of various territorial spatial consolidation scenarios on ecosystems through simulation and assessed ESV under different scenarios using models such as FLUS, which can capture its internal dynamics. However, compared to these models, the PLUS model distinguishes itself by employing a land expansion analysis strategy and a multi-type random patch generation mechanism. This makes it particularly well-suited for large-scale and complex simulations of various land types, offering enhanced simulation accuracy and rapid data processing capabilities. Therefore, this study considers Xinzheng City, a typical suburb in Henan Province. By analyzing the effects of PLE land use changes on ESV from 1980 to 2020 and simulating the spatiotemporal patterns of PLE land use under different scenarios in Xinzheng City in 2030 using the PLUS model, the study investigates the tradeoffs and synergies among ecosystem service functions. This work aims at promoting ecological safety patterns and optimizing territorial spatial patterns in metropolitan suburbs, with Xinzheng City serving as a case in point.

3. Theoretical analysis framework and research methods

This study employs the ESV assessment framework alongside tradeoff and synergy theory to delve into the ecosystem challenges in Xinzheng City. The PLUS model, ESV estimation techniques, and a spatial autocorrelation model are utilized. Initially, the status and evolution characteristics of the ecosystem in Xinzheng City during 1980–2020 are calculated. This analysis is conducted by incorporating local actual scenarios and utilizing the equivalent factor table. The PLUS model then simulates PLE land use under four distinct scenarios for 2030 and quantify ESV changes. Lastly, the spatial autocorrelation model is employed to unveil tradeoffs and synergies.

3.1 Theoretical analysis framework

Basically, the aim is to understand the relationship between different ecosystem services and to optimize the overall benefits derived from natural resources by studying the trade-offs and synergies between ecosystem services. To unveil these relationships, it is crucial to initially assess the ESV. Consequently, the theoretical framework of this paper encompasses two pivotal components: ESV assessment and tradeoff and synergy theory. These components collectively furnish the theoretical underpinning for methodological enhancements, content innovations in ESV assessment, and discussions on tradeoffs and synergies. They provide a robust and scientifically grounded conceptual foundation for this research.

3.1.1 ESV assessment

As one of the frontiers in ecological research, the focus of ESV assessment is undergoing a transformation from pure natural science to a domain that caters to societal ecological needs [37]. The ESV assessment method is utilized to predict changes in ESV values before and after the implementation of land use-related policies. These predictions draw from ESV theory, regional conditions, and local land use policies, enabling research into the ecological impacts of land-use change [38]. The methods of ESV assessment primarily include physical quantity, energy value, and value quantity assessments [39].

Physical quantity assessment is particularly well-suited for research at the regional and landscape scales, as it demonstrates substantial advantages in highlighting the heterogeneity and complexity of ecosystem service capabilities [40]. However, it is worth noting that this method may not be as intuitive and comprehensible as value quantity and energy value assessments when comparing different ecosystem service functions, primarily due to the utilization of various dimensional units [41]. Energy value assessments serve as means to convert diverse energy forms into a standardized unit. This approach holds promise in addressing the issue of repetitive calculations in ESV assessment.

Value quantity assessment is employed to measure various ecosystem services in a standardized monetary unit, and the assessment results present the cognitive strategies that align with the public. Costanza et al. (1997) calculated the ESV per unit area for various ecosystem services from equivalent results for function values of 17 ecosystem services worldwide. They subsequently converted the total ESV for each ecosystem service from a functional perspective, a widely adopted approach. Costanza et al. (2014) further revised the ESV equivalents in their previous research and calculated changes in ESV on a global scale from 1997 to 2011, utilizing updated land use data. In the early 21st century, Chinese researcher Xie et al. (2003; 2015) delved into the theory and calculation methods of ecosystem services functions with Costanza et al.'s research outcomes. They compiled the "Evaluation Table of Ecosystem Service Values Supplied by Per Unit Area of Terrestrial Ecosystem in China" tailored to China's specific conditions. This compilation laid the groundwork for calculating and assessing ESVs across a variety of spatial scales, such as state, province, and county, encompassing various ecosystem types such as cultivated land, forests, lakes, and deserts. Building upon these theories, the present study employs the equivalent factor table offered by Xie et al. as a reference. Evaluation of ESVs in accordance with the classification system of Costanza et al., offering insights into the spatiotemporal change characteristics and scenario predictions for the ESV associated with PLE land use changes in Xinzheng City, based on the PLE land use types and ecosystem types.

3.1.2 Analysis of ecosystem service tradeoff and synergy theory foundation

Ecosystem services serve as fundamental to human livelihoods and societies, meeting the basic needs for human survival and production, while fostering the collective development of human well-being and societal progress. It acts as an intermediary between the natural ecosystems and the socio-economic system, underscoring the holistic significance of research into ecosystem service tradeoffs and synergies. Therefore, this research domain spans multiple disciplines, including ecology, sociology, economics, and geography. Throughout the evolution of human society, people consistently seek to enhance their welfare by following Maslow's Hierarchy of Needs. Consequently, Their preferences for ecosystem services are ranked from highest to lowest from provisioning services, regulating services, cultural services and supporting services [42]. The ecological resource management decisions guided by this utility preference hierarchy may exacerbate the contradiction between supply services and other ecosystem services to a certain extent. Ecosystem services represent a pivotal factor in sustaining human welfare. From the perspective of welfare economics, the implementation of economic systems (including financial and monetary policies), political systems (including electoral and legal systems), and cultural systems (including moral concepts and customs) that prioritize human welfare indices can substantially influence how natural ecosystems are utilized and to what extent. These systems can impact the development trajectory of an ecosystem, consequently leading to tradeoffs among ecosystem services and influencing human welfare [43]. In addition, the production theory factors in microeconomics, which focuses on the equilibrium between the input and output of production factors, exert a certain guiding effect on ecosystem service tradeoffs and synergies. An essential principle guiding decision-makers is to work towards achieving sustainability and efficiency in ecosystem services, ultimately improving human welfare. To gain a deeper understanding of how economic factors intertwine with land use and ecosystem services, both local and general equilibrium models are employed to assess the relationship between currency and ecosystem services.

From a geographical perspective, exploring the trade-offs and synergies of ecosystem services encompasses natural and human systems and their interactions; therefore, major branches of geography, including physical geography, human geography, remote sensing, and geographic information systems, can make significant contributions. These contributions are regarded as core topics within the broader scope of comprehensive geographical research. In terms of the geographical direction of ecosystem services research, Li et al. (2014) discussed the imperative of establishing ecosystem service geography from the perspective of scientific and societal development needs [44]. Ecosystem service geography aims to investigate the interaction mechanisms between natural and human factors in the formation, dissemination, and utilization of ecosystem services, based on geographical principles and methodologies, so as further to investigate the spatio-temporal characteristics and regional disparities of ecosystems services. Therefore, in research on tradeoffs and synergies from a geographical standpoint, the spatiotemporal differentiation of ecosystem services, regional differences and spatial flows of ecosystem service supplies and benefits, analysis and simulation of benefits at different scales, and natural and human driving factors are not only the research entry points but also constitute the theoretical bases in this research field.

From an ecological perspective, in particular, research on ecosystem and landscape ecology is another crucial theoretical basis for investigations on ecosystem service tradeoffs and synergies. In the context of decisions related to ecological protection and land use planning, a deeper understanding of the relationship among natural diversity, ecological sustainability, and ESV is pivotal. Moreover, by comprehensively analyzing the fundamental principles governing ecological processes, such as material and information flow, we can improve the efficacy of decisions concerning ecosystem service tradeoffs and synergies.

Ultimately, this contributes to the advancement of human welfare.

3.1.3 Research framework

In this study, coupling ESV assessments with the tradeoff and synergy theory, we construct a research framework focused on predicting and analyzing tradeoffs and synergies within ecosystem services under multi-scenario land use changes (Fig. 1). This framework primarily consists of three key components: multi-scenario land use simulation, ESV assessment, and tradeoff and synergy analysis. Based on the future development goals of Xinzheng City, we define four distinct future land consolidation scenarios: natural development, urban development, cultivated land protection, and ecological protection. We utilize the Markov model and the PLUS model to predict the spatiotemporal evolution characteristics of ESVs in Xinzheng City for the year 2030 under these four scenarios. Furthermore, we reveal the tradeoffs and synergies among ecosystem service functions in Xinzheng City using spatial autocorrelation analysis and other relevant analytical methods. Finally, based on the previous research, this paper presents its research findings, further highlighting its shortcomings and potential avenues for future research. Moreover, the paper offers insights that can inform governmental decision-making, aiming to optimize policies and practices based on the research results.

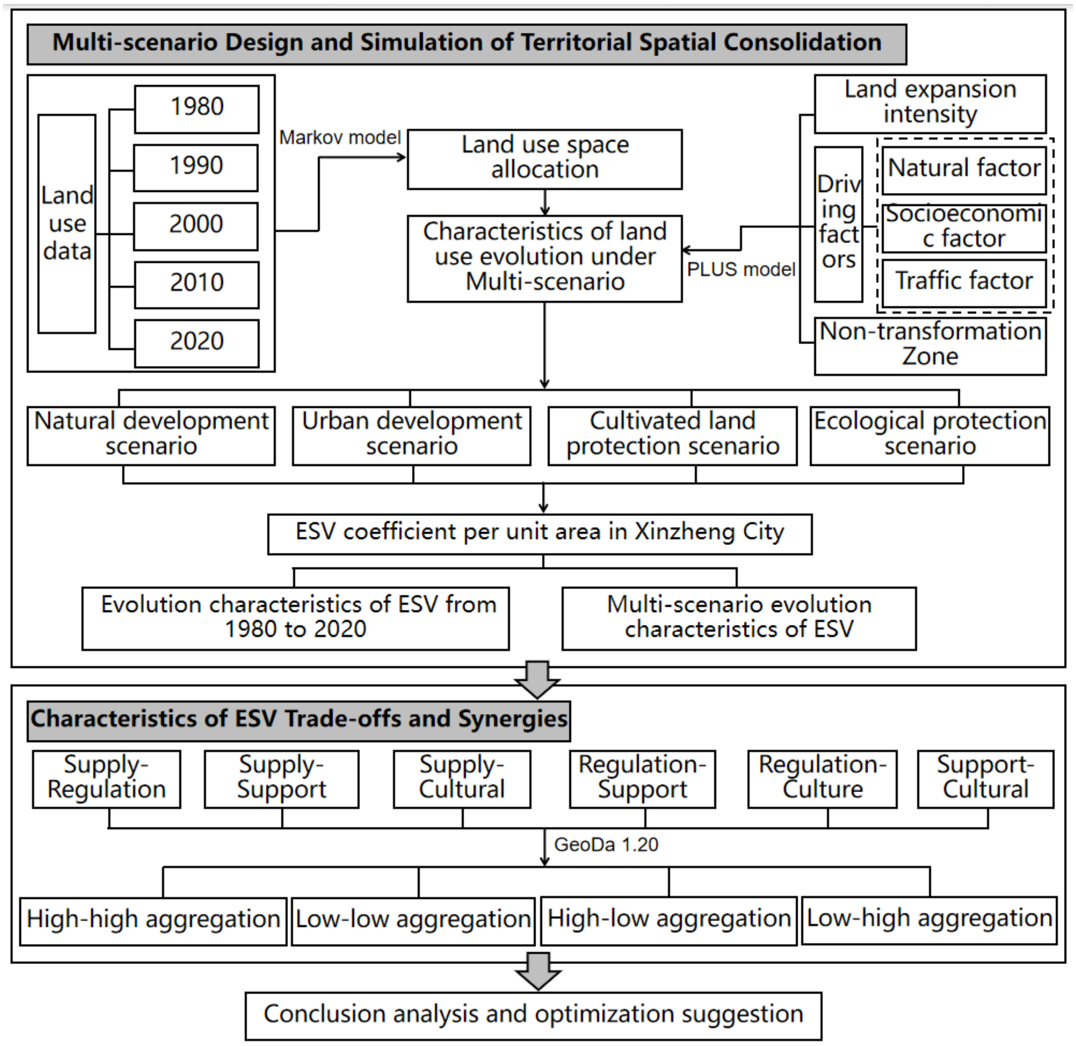

Figure 1. Research framework

3.2 Research methods

This paper employs three research methods: the PLUS model, ESV assessment, and spatial autocorrelation analysis. After classifying and extracting relevant data, we calculate the ecosystem service function equivalent value per unit of area in Xinzheng City, taking into account relevant studies. Subsequently, we simulate future land use changes under various scenarios using the PLUS model and discuss the spatial correlations among ESV functions.

3.2.1 PLUS model

The PLUS model, a novel approach, integrates the Cellular Automaton (CA) principle, which combines the driving factors suitability assessment of FLUS with the pattern operation of the Artificial Neural Network-based Cellular Automaton (ANN-CA) framework. This integration is achieved through the mutual transformation of different land use types among multi-period land use data [45]. Tilahun et al. (2016) demonstrated that the PLUS model could accurately describe the impact weights of the influencing variables of different land use types, thereby revealing the internal mechanisms governing territorial spatial evolution and effectively simulating the territorial spatial changes under various future policy scenarios [46].

(1) LEAS

The Land Expansion Analysis Strategy (LEAS) primarily focuses on analyzing land use data from two distinct periods and calculates based on the increased patches of each land use type, aiming to elucidate the evolution law of land use types and analyze the evolution characteristics within a specific time span. This strategy employs the Random Forest Classification (RFC) method to examine the relationship between driving factors and changes in different PLE land use types, thereby revealing the development law of each land use type.

$$P_{i,k(X)}^{d} = \frac{\sum_{n=1}^{M} I[h_n(X)=d]}{M} \quad (1).$$

In Formula (1), X and M represent the number of vectors and decision trees composed of driving factors, respectively. The value of d is 0 or 1, where 1 indicates that other land use types can be transformed into land use type k and 0 indicates that other land use types cannot be transformed into land use type k. h_n(x) represent the land use prediction type calculated when the decision tree is n. $\mathrm{Ih_n(X) = d}$ denotes the exponential function of the decision tree. $P_{i,k(X)}^{d}$ represents the growing probability of land use type k in the spatial unit i.

(2) CA Model (CARS)

The CA Model Based on Multi-class Random Patch Seed (CARS) model is a scenario-driven land use simulation model based on CA, which primarily focuses on simulating the distribution pattern of land use by determining the development probability of different land types. The total transformation probability of land use type k ($P_{o,i,k}^{d=1,t}$) is calculated as follows:

$$P_{o,i,k}^{d=1,t} = P_{i,k}^{d=1} \times \Omega_{i,k}^{t} \times \mathrm{D}_k^t \quad (2).$$

In Formula (2), $\mathrm{P_{i,k}^{d=1}}$ represents the growth probability of the PLE land type k in cell i. In $\Omega_{i,k}^{t}$, k represents the categorical action of cell i. $\mathrm{D_k^t}$ represents the impact value on the future demand for the PLE land type k and is calculated using Formula (4):

$$\Omega_{i,k}^{t} = \frac{con(c_i^{d=1}=k)}{n \times n - 1} \times \mathrm{W}_k \quad (3),$$

$$D_k^t = \begin{cases} D_k^{t-1} (\left|G_k^{t-1}\right| \le \left|G_k^{t-2}\right|) \\ D_k^{t-1} \times \dfrac{G_k^{t-2}}{G_k^{t-1}} (G_k^{t-1} < G_k^{t-2} < 0) \\ D_k^{t-1} \times \dfrac{G_k^{t-1}}{G_k^{t-2}} (0 < G_k^{t-2} < G_k^{t-1}) \end{cases} \quad (4).$$

In Formulas (3) and (4), *con* denotes the total number of cells occupied by the PLE land type k in the last repetitive calculation in the $n \times n$ value. W_k represents the weight of different PLE land use types, and its value is set to 1. $\mathrm{G_k^{t-1}}$ and $\mathrm{G_k^{t-2}}$ identify gaps in current and future demands for the PLE land type k calculated t-1 and t-2 times, respectively.

(3) Parameter settings

1) LEAS parameters: The values for the decision tree, sampling rate, and mTry parameters are set as 20, 0.01, and 14, respectively.

2) CARS parameters: The neighborhood range is set to 3, and the thread is set to 1. Additionally, the threshold decreasing coefficient, diffusion coefficient, and random patch seed probability are set to 0.5, 0.1, and 0.0001, respectively.

3) Scenario settings: This paper establishes four scenarios: natural development, urban development, cultivated land protection, and ecological protection. The natural development scenario continues the current development trend without any constraints. The urban development scenario leads to an increased proportion of production land transformed from cultivated land, forest land, and waters while restricting the transformation of production land into other land types. The cultivated land protection scenario prioritizes the protection of cultivated land and restricts its transformation into other land types. The ecological protection scenario focuses on restricting the transformation of ecological lands such as forest land, grassland, and waters into other land types.

(4) Simulation process and precision validation

First, 20% of the land use expansion data are selected as the fundamental data through random sampling, and the complex relationships between each land use type and various driving factors such as natural environment, social economy, and transportation are determined using the random forest algorithm. This helps to obtain the transformation probabilities of each land use type. Second, to validate the precision of the results, the neighborhood weights are established based on the transition rules of eight land use types in 2010 and 2020. The overall pattern of the simulation results in 2020 closely resembles the current land use status (Fig. 2). The simulation accuracy of the models is evaluated with an overall precision of 91.82% and a Kappa coefficient of 84.79%. These results indicate a small simulation difference, demonstrating that the PLUS model effectively reflects land use changes in Xinzheng City. Finally, land demand, the transfer cost matrix, and neighborhood weight indices are established in combination with the mechanisms of random seed generation and threshold reduction. This assists in simulating the land patches under different scenarios in Xinzheng City in 2030 under the constraints of development conditions.

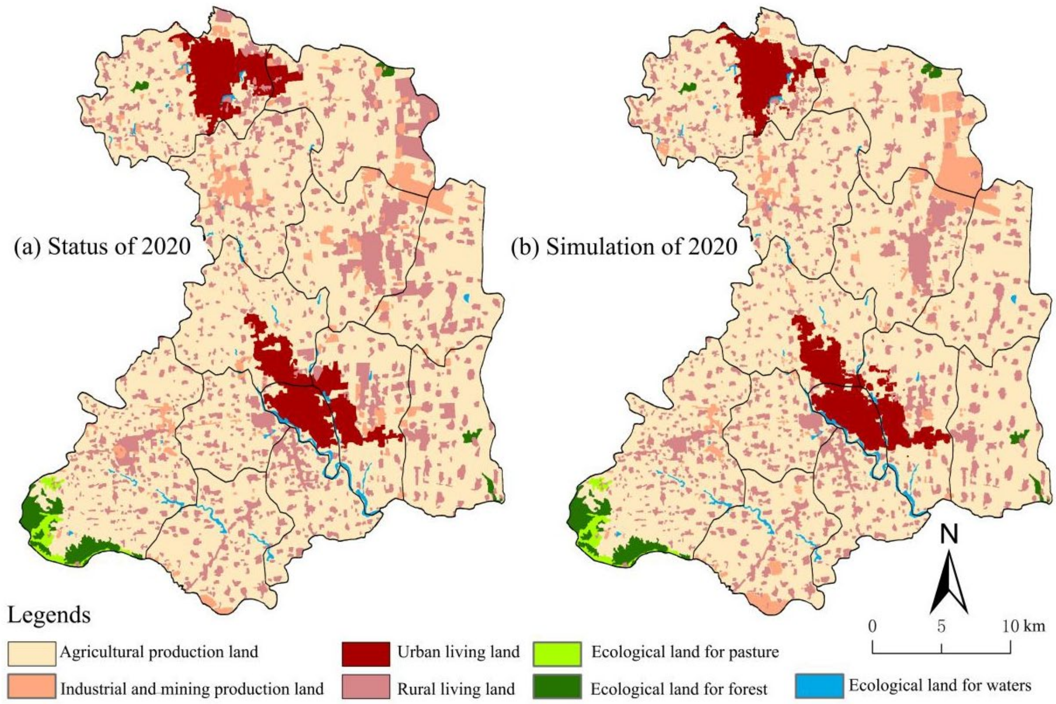

Figure 2. Comparison of the status and simulation precision of PLE land use in Xinzheng City in 2020

3.2.2 Calculation of ESV

Based on the principle that "the economic value of one unit of equivalent factor equals one-seventh (approximately 14.3%) the average market value of grain per unit of yield in Xinzheng City", we calculate the average annual economic value of natural grain produced per unit of farmland in Xinzheng City. To align more closely with the actual conditions in Xinzheng City, this research is adjusted using data on unit yield, planting area, and the economic value of food crops, as sourced from the *Xinzheng Statistical Yearbook* from 1980 to 2020. Seven average values are calculated, yielding an equivalent factor value of unit ESV of 218.66 dollars/hm^2 in the research area.

The ESV coefficient of Xinzheng City is computed based on the economic value of food crops per unit area of farmland and the equivalent factor table established by Xie et al. (2003; 2015) for each ecosystem service equivalent of the PLE land use (Table 1). Among them, agricultural production land, ecological land for forest, ecological land for pasture, ecological land for waters, and other ecological lands correspond to farmland, forest (coniferous and broad-leaved mixed forest) land, grassland, water area, and bare land, respectively, in the "Table of Equivalents of Ecosystem Service Values Supplied by Per Unit Area of Terrestrial Ecosystem in China." The proportion of paddy and dryland in Xinzheng City is used to adjust the equivalent value of agricultural production land. Urban and rural living land corresponds to deserts, while industrial and mining production land corresponds to bare land. The equivalent factor for water supply is determined based on the proportion of domestic water, industrial water, and agricultural water in the *China Water Resources Bulletin 2020*.

Table 1. Ecosystem service value (ESV) coefficient per unit area in Xinzheng City (USD/hm^2)

Classification		Supply services			Regulation services				Support services			Cultural services
Class I	Class II	Grain production	Raw material production	Water supply	Gas regulation	Climatic regulation	Environmental purification	Hydrological regulation	Soil conservation	Nutrient circulation	Biodiversity	Aesthetic landscape
	1	186.26	87.65	4.38	146.82	78.89	21.91	59.17	225.71	26.30	28.49	13.15

Production land	2	0	0	−289.25	4.38	0	21.91	6.57	4.38	0	4.38	2.19
Living land	3	2.19	6.57	−67.93	24.11	21.91	67.93	46.02	28.49	2.19	26.30	11.00
	4	2.19	6.57	−26.30	24.11	21.91	67.93	46.02	28.49	2.19	26.30	10.96
Ecological land	5	83.27	122.71	67.93	431.69	1141.68	376.91	837.08	525.92	39.44	477.71	210.37
	6	63.55	144.63	74.50	475.52	1424.36	422.92	1038.68	580.70	43.83	528.11	232.28
	7	175.30	50.40	1816.60	168.73	501.81	1216.18	22404.03	203.79	15.34	558.78	414.16
	8	0	0	0	4.38	0.00	21.91	6.57	4.38	0	4.38	2.19

3.2.3 Quantitative expression of ecosystem service tradeoffs and synergies

Spatial autocorrelation comprises global and local autocorrelation, with the latter further divided into single- and multi-variable autocorrelation. In this paper, bivariate spatial autocorrelation analysis is employed. Compared with the exponential analysis of other non-spatial expressions, bivariate autocorrelation analysis provides a more intuitive representation of the research area's correlations using the Local Indicators of Spatial Association (LISA) map [47]. This analysis yields six groups of correlation relationships through a pairwise combination of four ecosystem services. These six groups of correlation data, under the four scenarios, are processed using GeoDa 1.20 software, ultimately yielding the correlation degree of the two variable attributes under various scenarios. The calculations for bivariate global and local autocorrelation models are performed as follows:

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(y_i^m - \bar{y}_m)(y_j^z - \bar{y}_z)}{(\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij})\sum_{i=1}^{n}(y_i^m - \bar{y}_m)(y_j^z - \bar{y}_z)} \quad (5),$$

$$I_{ij} = Q_i^m \sum_{j=1}^{n}(w_{ij}Q_j^z); Q_i^m = \frac{y_i^m - \bar{y}_m}{\sigma_m}; Q_j^z = \frac{y_j^z - \bar{y}_z}{\sigma_z} \quad (6),$$

where I represents the bivariate global spatial autocorrelation index, n represents the number of grid cells, w_{ij} represents the weight, y_i^m represents the m attribute value of the ith grid cell, y_j^z represents the z attribute value of the jth grid cell, $\bar{y}_\mathrm{m}$ represents the average value of the attribute m, $\bar{y}_z$ represents the average value of the attribute n, I_{ij} represents the bivariate local spatial autocorrelation index, σ_m represents the variance of the attribute m, and σ_z represents the variance of the attribute z.

4. Overview of the research area and data sources

The study presents a detailed depiction of the regional landscape in Xinzheng City using the theoretical framework and methodologies outlined. The primary data for this assessment are sourced from local remote sensing satellite imagery. A series of pre-processing steps are meticulously undertaken to evaluate the regional ESV.

4.1 Overview of the research area

Xinzheng City located to the south-east of Zhengzhou City (E113°30'–113°54', N34°16'–34°39') at the transition zone between the Funiu Mountain area in western Henan Province and the North China Plain in eastern Henan Province. The topography of Xinzheng City varies, with higher elevations west and lower elevations east, spanning from 85 to 773 m. The county has a population of approximately 1,172,200 individuals and covers a total area of 873 km^2. Xinzheng City has experienced rapid urbanization owing to the construction of the Zhengzhou metropolitan area and the Zhengzhou Airport Economy Zone. It serves as a significant hub for national transportation infrastructure and industrial expansion. The county ranks among the top 100 counties in terms of county-level economic performance and overall competitiveness. In 2021, its total gross domestic product (GDP) reached 10.854 billion dollars, securing its position as the top-ranking county-level economy in Henan Province for three consecutive years. In recent years, Xinzheng City has witnessed substantial changes in its territorial space, which could be largely attributed to the continuous northward expansion of the university town in Longhu Town, the Zhengzhou Airport Economy Zone, and the main urban area. These changes have exerted increased pressure on the city's ecological environment at the county level. Therefore, this research on impacts of territorial spatial evolution on ecosystem services serves as a typical demonstration of ecological safety pattern construction in metropolitan suburbs.

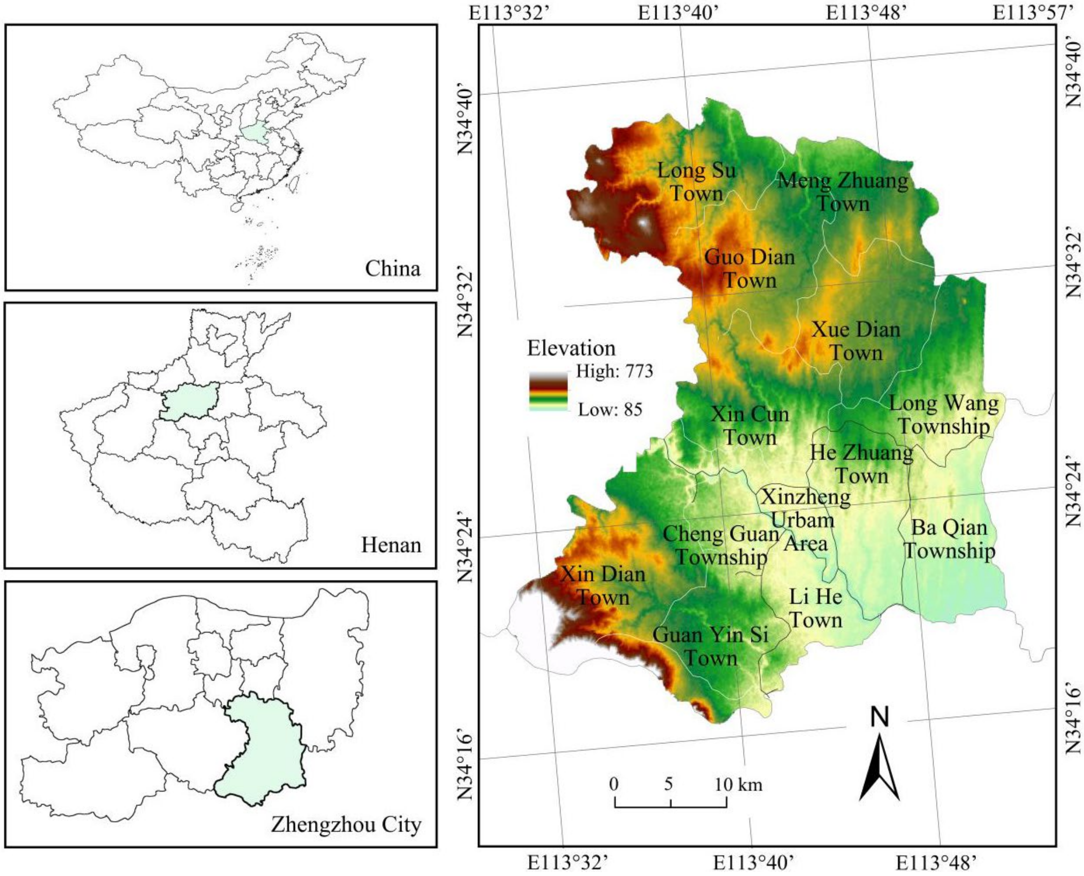

Figure 3. Location of the research area

4.2 Selection of land use change factors

Existing research results have demonstrated that land use change is a multifactorial process influenced by various interconnected factors. In this study, considering the actual conditions in Xinzheng City, the driving factors influencing land use change are selected from three dimensions: natural environment, social economy, and transportation. These factors are selected based on data availability and quantification of driving factors. Moreover, policy factors are incorporated into the simulation to align with the scenario principle and China's land and urban planning constraints (Table 2).

To ensure the appropriateness of the selected driving factors, their correlation with changes in the PLE land use types is assessed using logistic regression analysis. The receiver operating characteristic values for all types of land use are above 0.75, suggesting that these factors effectively represent land use change in the assessment domain.

Table 2. Selection and description of driving factors of PLE land use change in Xinzheng City

	Driving factor	Description of factor
Natural factor	Elevation	30 m × 30 m DEM data published by the Geospatial Data Cloud
	Slope	Obtained by surface treatment using ArcGIS10.8
	Slope direction	Obtained by surface treatment using ArcGIS10.8
Socioeconomic factor	Population per unit area	Spatialize the population using the grid and the PLE land use data based on data obtained from the *Xinzheng Statistical Yearbook*
	GDP per unit area	Spatialize the GDP using the grid and the PLE land use data based on data obtained from the *Xinzheng Statistical Yearbook*
Transportation factor	Distance to the county	Distance to the city government
	Distance to roads	Distance to expressways, national highways, and railways
	Distance to water areas	Distance to rivers and lakes

4.3 Data sources

The required data for this study can be categorized into basic data and driving factor data. Basic data, primarily composed of land use data, include 6 first-class factors and 25 second-class factors. Driving factor data include data related to the natural environment (elevation, slope, slope direction, and accumulated temperature), social economy (farmland productivity potential, population density, and per capita GDP), and transportation location (distance to the county center, distance to highways, distance to national highways, and distance to railways). The administrative district boundary data were obtained from the National Geomatics Center of China (https://www.ngcc.cn/ngcc/), while land use data covering five periods from 1980 to 2020, and data related to the natural environment and socioeconomic factors, were obtained from the Resource and Environment Science and Data Center (https://www.resdc.cn/). Additionally, vector data, including transportation location data, were sourced from OpenStreetMap.

The theory of PLE space was formulated with the multi-functionality of land use, and their connotations were consistent. PLE space is a functional space divided by the services and functions of land use, and it can be seamlessly and effectively associated with the territorial spatial planning system under the current reform. Therefore, based on the research on the construction of the PLE space classification system for the existing land use types, it explores the attributes and scenario simulations of land use change in PLE space in Xinzheng City. It further establishes a classification system for the dominant functions of PLE space in Xinzheng City, guided by the principles of dominant function and operability (Table 3).

Table 3. Classification of dominant functions of PLE space

Dominant classification: Class I	Dominant classification: Class II	Secondary land types in the land use classification system	Basis of classification
Production land	1 Agricultural production land	Paddy field and arid land	With the supply of agricultural products as the mainstay; belonging to agricultural production land
	2 Industrial and mining production land	Industrial and transportation construction land, such as quarry, industrial zone, and airport lands	Factory and mine, industrial zone, land for roads, and other lands used for special purposes
Living land	3 Urban living land	Urban land	Built-up area lands in large-, medium-, and small-sized cities and above county and town level
	4 Rural living land	Land for rural residents	Places supporting the residence, life, production, and cultural activities of rural residents
Ecological land	5 Ecological land for pasture	High-, medium-, and low-coverage grasslands	Grasslands dominated by herbaceous plants and with a coverage of more than 5%
	6 Ecological land for forest	Forest land, shrub land, open forest land, and other forest lands	Forestry lands with arbors, shrubs, and bamboo
	7 Ecological land for waters	River and canal, lake, reservoir pit, and beach land	To regulate regional temperature and local climate and maintain the ecological safety of water areas
	8 Other ecological lands	Sandy land, Gobi desert, marshland, bare land, bare rock stony land, etc.	Unused land at present, including those difficult to be used

4.4 Data processing

In this paper, radiometric calibration and atmospheric correction are applied to the remote sensing data for each time period. Following the guidelines outlined in the *Current Land Use Classification* (GB/T1980-2020) and using a combination of maximum likelihood classification and visual interpretation, the land use coverage is categorized into eight types: agricultural production land, industrial and mining production land, urban living land, rural living land, ecological land for pasture, ecological land for forest, ecological land for waters, and other ecological lands. The interpretation results are verified with high-resolution images from Google Earth. The overall classification precision for the five-phase remote sensing images is 30 m, with an interpretation precision of 88.95%.

5. Empirical results and analysis

The territorial spatial structure and ESV evolution characteristics of land use in Xinzheng City during 1980–2020 are calculated using data derived from remote sensing image interpretation. Furthermore, the study employs PLUS model in simulating the spatio-temporal pattern of ESV in Xinzheng City for various scenarios for the year 2030. Additionally, the tradeoffs and synergies among various ecosystem service functions in Xinzheng City are revealed by employing the spatial autocorrelation method.

5.1 Evolution characteristics of production–living–ecological land use in Xinzheng City

Table 4 reveals significant changes in land use patterns in Xinzheng City from 1980 to 2020. During this period, the area of industrial and mining production land and urban residential land expanded rapidly, while the area of agricultural production land and ecological forest area decreased significantly. The area of agricultural production land, which constituted the highest proportion (averaging 75.32%), consistently decreased over the four decades, with a total reduction of 9,425.74 hm^2. Meanwhile, the area of ecological land for forest decreased sharply, plummeting from 5,445 hm^2 to 1,210.41 hm^2. Driven by the continuous promotion of policies such as the construction of the Zhengzhou metropolitan area and the third phase of Zhengzhou Xinzheng International Airport, the expansion of industrial, mining, and urban residential land also accelerated. Over the research period, the area of these two land types increased by 3,698.88 hm^2 and 5,319.27 hm^2, respectively, representing a remarkable growth rate of 1,446.46% and 1,137.25%, respectively. The area of ecological land for waters exhibited an initial decline, followed by a slight increase, while the share of unutilized space remained comparatively modest.

Considering 2020 as the reference year, the study simulates the characteristics of PLE land use changes in Xinzheng City under the four scenarios for the year 2030. The statistical results indicate that compared to those in 2020, under the natural development scenario for 2030, the area of industrial and mining production land is projected to experience the most significant increase (36.15%), with an increase of 1,429.64 hm^2; urban and rural living land will experience a slight increase; and agricultural production land will undergo remarkable changes, witnessing a total reduction of 2,670.56 hm^2. Under the urban development scenario, the areas of industrial and mining production land and urban living land are projected to experience the most significant increase (45.24% and 16.14%, respectively); ecological land for pasture and waters will increase slightly; and agricultural production land is estimated to experience the most significant decrease, with a total reduction of 3,055.36 hm^2. Under the cultivated land protection scenario, agricultural production land and urban living land are estimated to increase by 959.24 hm^2 and 124.59 hm^2, respectively, whereas the areas of rural living land and industrial and mining production land are projected to decrease by 740.09 hm^2 and 185.58 hm^2, respectively. Under the ecological protection scenario, ecological land for pasture is expected to exhibit the most significant increase, with a growth rate of 44.12%. In contrast, the areas of agricultural production land and ecological land for forest will experience an evident decrease, whereas the areas of industrial and mining production land and other ecological lands will experience slight changes by 2030.

Table 4. Statistics on the areas of various land use types in Xinzheng City from 1980 to 2030/hm^2

Year/Scenario	Production land		Living land		Ecological land			
	Agricultural production land	Industrial and mining production land	Urban living land	Rural living land	Ecological land for pasture	Ecological land for forest	Ecological land for waters	Other ecological lands
1980	70604.5	255.72	467.73	9978.21	846.36	5445	761.49	0.09
1990	66725.29	1703.34	2472.03	11718.81	565.74	4448.52	725.31	0.06
2000	67883.13	2272.45	3643.92	12104.46	481.32	1233.09	740.7	0.03
2010	66338.15	2485.8	4538.25	12526.47	481.32	1233.27	755.82	0.02
2020	61178.76	3954.6	5787	14985.99	484.02	1210.41	758.25	0.02
Natural development scenario	58508.2	5384.24	6595.01	15410.50	482.83	1199.49	778.79	0.01
Urban development scenario	58123.40	5743.80	6721.22	15318	503.06	1175.26	774.31	0.01
Cultivated land protection scenario	62138.00	3769.02	5911.59	14245.90	435.24	1101.98	757.32	0.02
Ecological protection scenario	58495.30	4442.51	6360.56	16540.6	697.591	1048.07	774.434	0.03

5.2 Dynamic evolution characteristics of ESV in Xinzheng City

5.2.1 Evolution characteristics of ESV from 1980 to 2020

Herein, a 300 m × 300 m grid was created using the fishnet tool of ArcGIS, the ESV was calculated at the grid scale, the spatial distribution map of the ESV in Xinzheng City from 1980 to 2020 was prepared, and the ESVs were classified in five categories, ranking from lowest to highest, according to the Natural Breakpoint Method (Fig. 3). As evident from Table 5, the total ESV in Xinzheng City decreased from 116 million dollars in 1980 to 85.78 million dollars in 2020, experiencing a continuous decline of 30.1 million dollars. When analyzing each specific decade, it was observed that from 1980 to 1990, both ecological land and agricultural production land exhibited a substantial decrease in ESV, totaling 8.35 million dollars. From 1990 to 2000, the ESV decreased primarily for ecological land for forests and waters, resulting in a loss of 29.42 million dollars, which was the most substantial loss observed during this period. This can primarily be attributed to the construction of the Zhengzhou Airport Economy Zone, which led to the transformation of ecological land for forests and waters into urban living land and industrial and mining production land. After 2000, the ESV displayed an overall gradual decrease. Although the ESV of agricultural production land continued to decrease, that of ecological land for waters increased considerably, which contributed to the overall stability of the ESV during this period. This shift can be attributed to the conclusion of infrastructure construction in Xinzheng City and the initial construction of Xinzheng International Airport. Meanwhile, ongoing projects such as the construction of Xinzheng Xuanyuan Lake Wetland Park and Longhu Wetland Park and ecological management projects of Shuangji River and Meihe River are under continuous advancement. These endeavors contribute to the formation of blue and green landscapes in both urban and rural areas, effectively mitigating the overall loss in ESV to a greater extent.

We observed that during the research period and at the spatial evolution level (Fig. 4), the low-ESV areas in Xinzheng City were primarily concentrated in the vicinity of Zhengzhou Airport Economy Zone and Guodian Town Logistics Park and continued to expand over time. This expansion can be attributed to the predominant use of these areas as industrial and mining production land; moreover, the provision of water supply services in these areas displayed a notable negative effect on ESV. The low-ESV areas corresponded to the evolution pattern of urban and rural living land in the study area and continued to expand in tandem with urban expansion. In contrast, areas with moderate ESVs were most widely distributed and primarily dominated by agricultural production land. Some of these areas witnessed encroachment by urban expansion and industrial and mining production land use over time, leading to a continuous decrease in ESV in these areas. The high- and higher-ESV areas coincided with the distribution of ecological land for waters and forest and were concentrated in Shizu Mountain National Forest Park in the north and areas near the main urban center, including Shuangji River, Huangshui River, and Yishui River, during the research period. However, the high-ESV areas in the north gradually disappeared after 1990 owing to the continuous progress of the construction of the Zhengzhou Airport Economy Zone and Xinzheng New Urban Area.

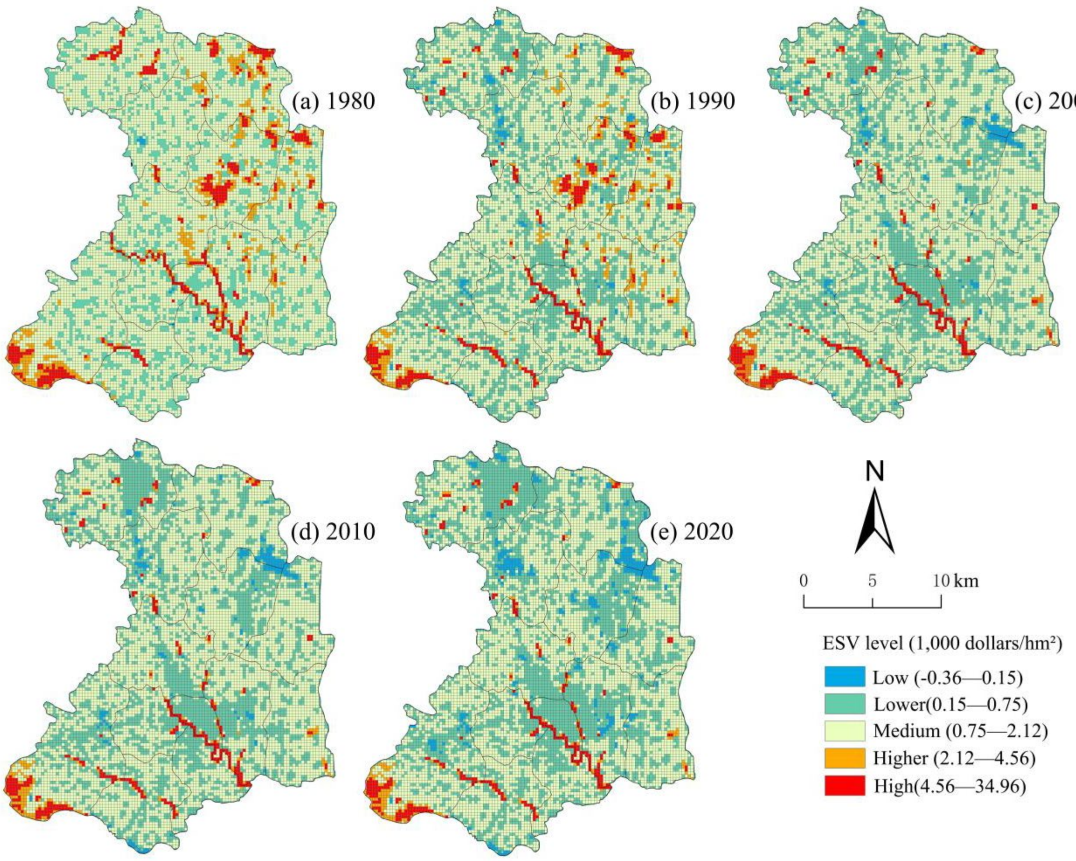

Figure 4. Spatial distribution of ecosystem service values (ESVs) in Xinzheng City from 1980 to 2020

Table 5. ESVs and changes in various land use types in Xinzheng City from 1980 to 2020 (unit: 10^4 USD)

Land use type	Ecosystem service value					Change				
	1980	1990	2000	2010	2020	1980–1990	1990–2000	2000–2010	2010–2020	1980–2020
Agricultural production land	6206.72	5865.71	5967.49	5831.69	5378.19	–341.02	101.78	–135.80	–453.50	–828.53
Industrial and mining land	–6.31	–41.84	–55.83	–61.04	–97.12	–35.53	–13.99	–5.21	–36.08	–90.81
Urban living land	7.96	41.70	61.45	76.54	97.67	33.74	19.75	15.09	21.12	89.71
Rural living land	210.01	246.64	254.73	263.65	315.36	36.63	8.09	8.92	51.71	105.35
Ecological land for pasture	365.29	244.17	207.82	207.82	208.92	–121.12	–36.35	0.00	1.10	–156.38
Ecological land for forest	2739.51	2238.13	620.44	620.44	608.92	–501.37	–1617.70	0.00	–11.52	–2130.59
Ecological land for waters	2096.84	1997.26	667.90	2081.34	2087.93	–99.59	–1329.36	1413.44	6.58	–8.92

Other ecological lands	0.00041	0.00027	0.00014	0.00014	0.00014	–0.00014	–0.00014	0.00000	0.00000	–0.00027
Total	11620.16	10591.91	9095.88	9020.44	8600.00	–1028.26	–1496.02	–75.45	–420.44	–3020.16

The functions and changes of ESV are presented in Table 6. Throughout the investigation periods, the functions of hydrological regulating and soil conservation consistently accounted for a greater proportion of ESV, followed by the functions of climatic regulation, grain production, gas regulation, and other functions, which had a relatively lower proportion. Over the past 40 years, all ESV functions in Xinzheng City exhibited varying degrees of decline. Among these, climatic regulation, hydrological regulation, and soil conservation ESVs were −7, −4.79, and −4.38 million dollars, respectively. This decline was especially notable from 1990 to 2000, primarily due to the expansion of Longhu Town Industrial Park and Xincun Town Industrial Park during this period, leading to a large-scale increase in industrial and mining production land and urban construction land. However, after 2000, the decrease in ESV witnessed a sharp reduction, and in some cases, the ESV for certain land types increased slightly due to the transformation of major wetland parks and water systems.

Table 6. Variation in ESV of various functions in Xinzheng City from 1980 to 2020 (unit: 10^4 USD)

Function	ESV of a single item					Variation				
	1980	1990	2000	2010	2020	1980–1990	1990–2000	2000–2010	2010–2020	1980–2020
Grain production	1372.98	1292.18	1293.28	1265.02	1169.55	–80.80	1.10	–28.26	–95.47	–203.43
Raw material production	719.07	669.41	633.06	620.58	577.37	–49.66	–36.35	–12.48	–43.21	–141.70
Water supply	178.88	101.10	54.46	43.21	–16.19	–77.78	–46.64	–11.25	–59.40	–195.06
Gas regulation	1370.78	1263.37	1127.98	1108.78	1041.70	–107.41	–135.39	–19.20	–67.08	–329.08
Climatic regulation	1490.95	1292.59	838.13	829.63	794.24	–198.35	–454.46	–8.50	–35.39	–696.71
Environmental purification	581.21	544.31	421.26	429.08	445.68	–36.90	–123.05	7.82	16.60	–135.53
Hydrological regulation	2809.60	2596.71	2304.39	2335.39	2326.20	–212.89	–292.32	31.00	–9.19	–483.40
Soil conservation	2000.55	1850.89	1690.81	1660.08	1553.50	–149.66	–160.08	–30.73	–106.58	–447.05
Nutrient circulation	216.46	201.51	190.53	186.69	173.94	–14.95	–10.97	–3.84	–12.76	–42.52
Biodiversity	599.45	530.86	365.43	365.43	360.22	–68.59	–165.43	0.00	–5.21	–239.23
Aesthetic landscape	280.25	248.97	176.54	176.68	173.80	–31.28	–72.43	0.14	–2.88	–106.45
Total	11620.16	10591.91	9095.88	9020.44	8599.86	–1028.26	–1496.02	–75.45	–420.58	–3020.30

5.2.2 Multi-scenario evolution characteristics of ESV from 2020 to 2030

Table 7 reveals that in 2030, compared to the ESV status in 2020, under the natural development scenario, the decrease in the ESV of agricultural production land and ecological land for pasture is estimated to be less than the increase in the ESV of ecological land for forest and waters, resulting in a total ESV decrease of 1.09 million dollars. In contrast, the urban development scenario exhibits the lowest ESV among all scenarios, showing a decrease of 1.68 million dollars compared to that in 2020. The most substantial decrease in ESV is estimated to occur in agricultural production land (2.68 million dollars). In cultivated land protection scenario, the ESV is the highest among all scenarios, increasing by 0.84 million dollars compared to that in 2020. However, this increase is mainly attributed to drastic changes in agricultural production land. The ecological protection scenario witnesses an increase in the ESV of ecological land for pasture and waters but a significant decrease in the ESV of agricultural production land (–2.35 million dollars). Consequently, the total ESV is estimated to remain higher than those under the scenarios of urban development and natural development and lower than that observed in 2020. Therefore, ensuring the stable and sustainable growth of the ecosystem in Xinzheng City can only be guaranteed by preventing the encroachment of agricultural production land and by further coordinating ecological land such as forest land, pasture, and waters.

Table 7. Simulation of ESV of various land use types under four development scenarios in 2030 (unit: 10^4 USD)

Type	Production land		Living land		Ecological land				Total
	Agricultural production land	Industrial and mining production land	Urban living land	Rural living land	Ecological land for pasture	Ecological land for forest	Ecological land for waters	Other ecological lands	
Status of 2020	5378.19	–92.59	99.73	299.86	187.93	554.46	2085.46	0.00	8513.03
Natural development scenario	5143.35	–132.24	111.39	324.28	208.37	603.43	2144.58	0.00	8403.29
Urban development scenario	5109.60	–141.02	113.44	322.36	217.15	591.36	2132.24	0.00	8344.99
Cultivated land protection scenario	5462.55	–92.59	99.73	299.86	187.93	554.46	2085.46	0.00	8597.39
Ecological protection scenario	5142.25	–109.05	107.41	348.15	301.10	527.30	2132.51	0.00	8449.66

Figure 5 illustrates that the changes in ESV between 2020 and 2030 vary considerably across different scenarios. Notably, the urban development scenario experiences the highest decrease in ESV. The areas displaying significant decreases are concentrated in the industrial parks located in the northeast of the main urban area, southwest of Zhengzhou Xinzheng International Airport, Guodian Town Logistics Park, and the intersection of Mengzhuang Town, Xuedian Town, and Longwang Township. These areas correspond to the primary directions of urban development and are likely to exert a negative impact on Xinzheng City's ecosystem. Consequently, it is imperative to prioritize ecological restoration in these areas in the future. Under the cultivated land protection scenario, the ESV is projected to experience the lowest decrease and slight increases in some areas. This phenomenon is primarily attributed to the fact that agricultural production land accounts for 70% of Xinzheng City's land. The strict policy of protecting arable land is reducing the rate at which arable land is used and is placing restrictions on the expansion of building land. However, some ecological areas in the north, such as Shizu Mountain National Forest Park, Shuangji River, Huangshui River, and Yishui River, face substantial occupation challenges without adequate protection. In comparison, the ecological protection scenario, characterized by strict ecological protection policies, results in a low occupancy rate of ecological land for forest and pasture. However, cultivated land remains vulnerable to encroachment by construction land expansion. Consequently, the ESV in Zhengzhou Airport Economy Zone and Guodian Town in the north, which are in proximity to the main urban area of Xinzheng City, has experienced a decrease. Finally, the natural development scenario sees a downtrend in ESV, with the decrease range closely resembling that of the urban development scenario. However, the rate of decrease in ESV is relatively weak.

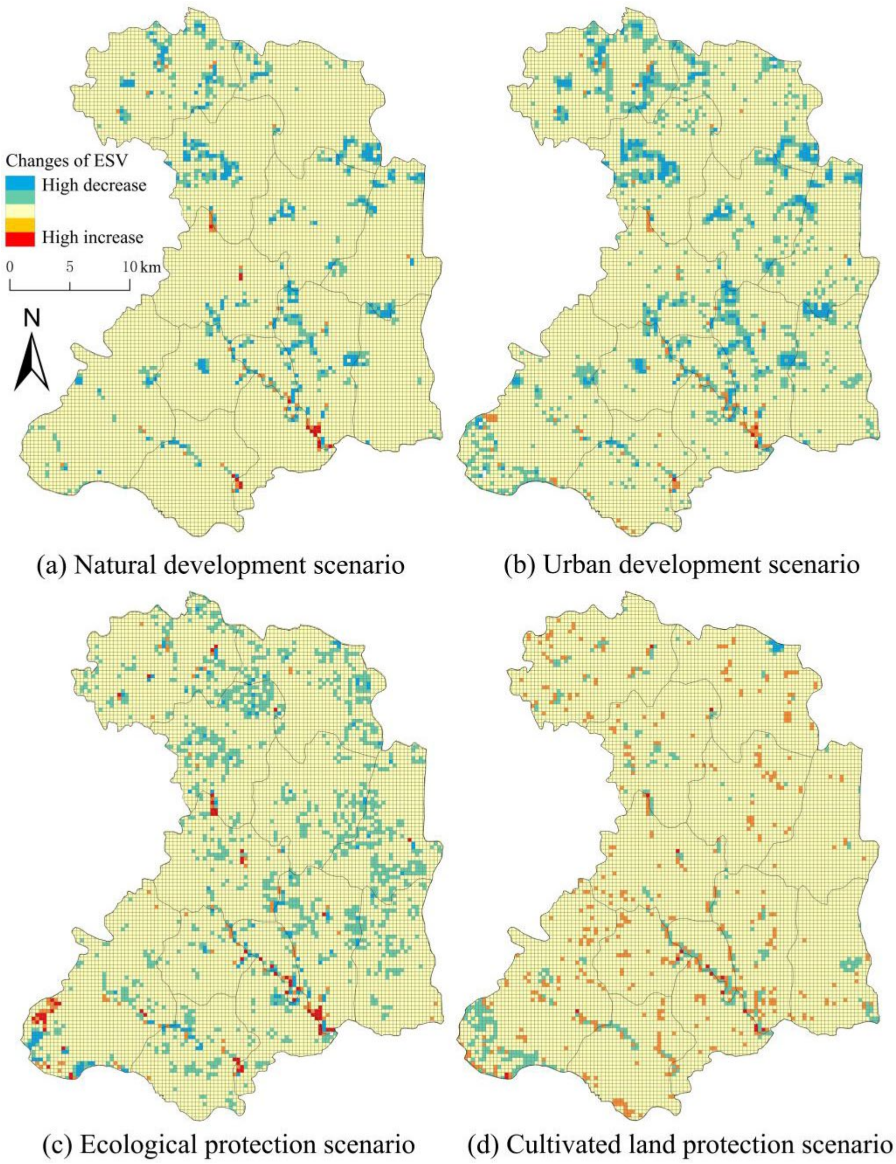

Figure 5. Changes in ESV in Xinzheng City from 2020 to 2030

Figure 6 illustrates changes in ESV under the four scenarios from 2020 to 2030 from the perspective of supply services. It is evident from the figure that the supply ESV is estimated to increase remarkably in cultivated land protection scenario, with a total increase of 280,024.63 dollars. Owing to the impact of the cultivated land protection policy, there has been a slight increase in the area of agricultural production land, as indicated in Table 6. This expansion, coupled with the improvement of ecological environment quality, will facilitate a continuous increase in the ESV of supply services. In scenarios of urban development and natural development, urban development is estimated to lead to the encroachment of large portions of ecological land and agricultural production land, thereby reducing the ESV of raw material production and food production services. Conversely, the ecological protection scenario, while regulating ecological land, will witness a remarkable reduction in the agricultural production land, causing the ESV to decline in comparison to that in 2020 under these three scenarios. In terms of regulation services, the ESV is estimated to decrease to a certain extent under all scenarios, with the ESV under the urban development scenario showing the most remarkable decline. Although the ecological protection scenario exhibits a positive regulation effect on the regional ecosystem, the significant reduction in agricultural production land within this scenario will still result in an overall ESV decrease of 23,190.58 dollars. The change characteristics in ESV of support services closely resemble those for supply services as a whole. Across the four scenarios, the ESV increases solely under the cultivated land protection scenario (by 55,999.45 dollars), while decreasing by more than 0.55 million dollars under other scenarios. In terms of the ESV of cultural services, the ecological protection scenario results in higher ESV for ecological land for forests and waters. Despite being affected by the decrease in agricultural production land, the overall ESV has increased by 3,406.76 dollars compared to that in 2020. However, this increase is primarily driven by the aesthetic landscape function to a certain extent under this scenario.

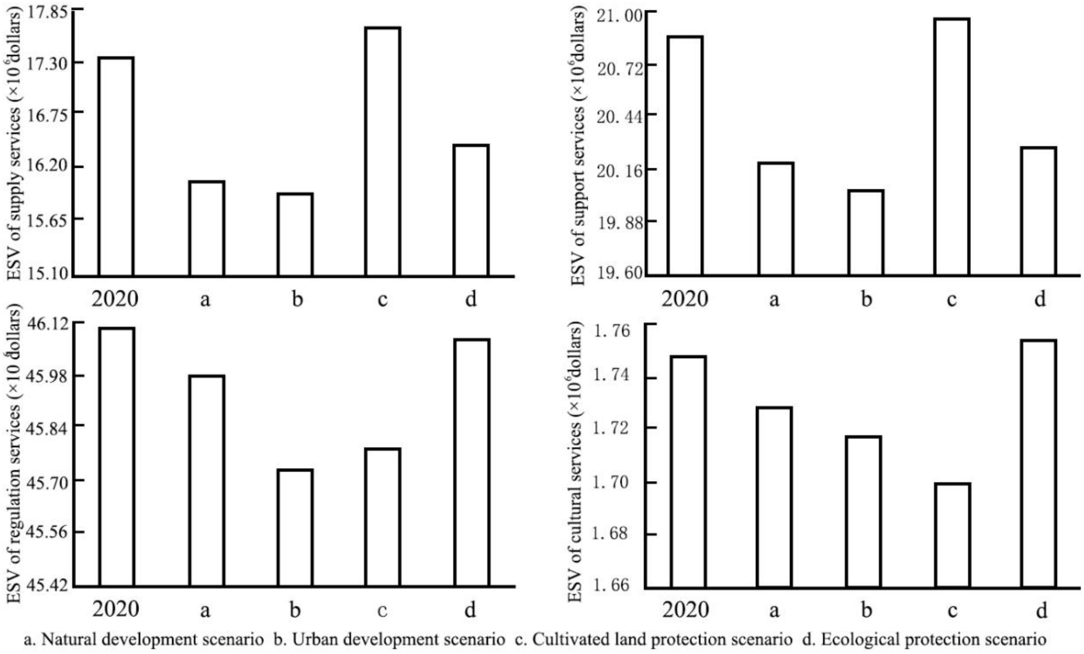

Figure 6. Changes in ESV in supply, regulation, support, and culture services under four scenarios in 2030

5.3 Characteristics of ESV tradeoffs and synergies

To explore the tradeoffs and synergies of ESV under multiple scenarios, we calculated the grid area ESV of supply, regulation, support, and culture services at the grid unit scale under the four scenarios. Subsequently, we conducted a bivariate global autocorrelation analysis. From Table 8, based on the bivariate global autocorrelation Moran's I index for four scenarios, supply, regulation, support and cultural services in Xinzheng City show consistent synergies. Among these scenarios, the cultivated land protection scenario displays the most significant synergies, and the spatial significance of synergy follows the order of support–culture services > supply–support services > regulation–culture services > regulation–support services > supply–regulation services > supply–culture services.

Table 8 Correlation analysis and statistics of four ecosystem services under different scenarios in Xinzheng City in 2030

Ecosystem services	Moran's I					
	Supply–Regulation	Supply–Support	Supply–Culture	Regulation–Support	Regulation–Culture	Support–Culture
Natural development scenario	0.258	0.370	0.222	0.235	0.373	0.520
Urban development scenario	0.255	0.379	0.222	0.234	0.371	0.513
Cultivated land protection scenario	0.257	0.382	0.223	0.321	0.376	0.518
Ecological protection scenario	0.261	0.357	0.221	0.236	0.370	0.520

To further explore the differentiation characteristics of tradeoffs and synergies at the grid scale across different ESV functions, we chose the cultivated land protection scenario, which exhibited the highest ESV and stronger autocorrelation compared to other scenarios, as an example. We conducted a local bivariate autocorrelation analysis among supply, regulation, support, and culture services using GeoDa 1.20 to generate the LISA map.

As evident from Fig. 7, there exist significant spatial aggregation characteristics for tradeoffs and synergies among the four ESV functions. The order by the degree of synergy is as follows: regulation–support services, supply–support services, supply–regulation services, regulation–culture services, support–culture services, and supply–culture services. The numbers of grids exhibiting synergies are 2,029, 1,971, 1,955, 1,513, 1,417, and 1,393, respectively, whereas the numbers of grids exhibiting tradeoffs are 337, 213, 396, 155, 276, and 372, respectively. Concerning the spatial distribution, the synergies between the areas located in the Southwest, such as Shizu Mountain National Forest Park, Shuangji River, Tangzhai Reservoir, Yangzhuang Reservoir, and Wuhuzhao Reservoir, are characterized by high–high aggregation, larger ecological spaces of forest land and waters, minimal human activities, and higher ESV quality. However, the synergies among areas such as Zhengzhou Airport Economy Zone, Guodian Town Logistics Park, as well as the main urban area of Xinzheng City and Longhu Town, under the functions of supply–regulation, supply–support, and regulation–support services are characterized by low–low aggregation, which could be attributed to the consistent expansion of low-ESV areas caused by continuous development of industrial and mining production land and urban construction land. The tradeoffs are insignificant and are primarily distributed around the Shuangji River in the main urban area of Xinzheng City. These tradeoffs are greatly influenced by human socioeconomic activities, particularly along the ecosystem structure on both sides of the water systems, which exhibit tradeoff characteristics.

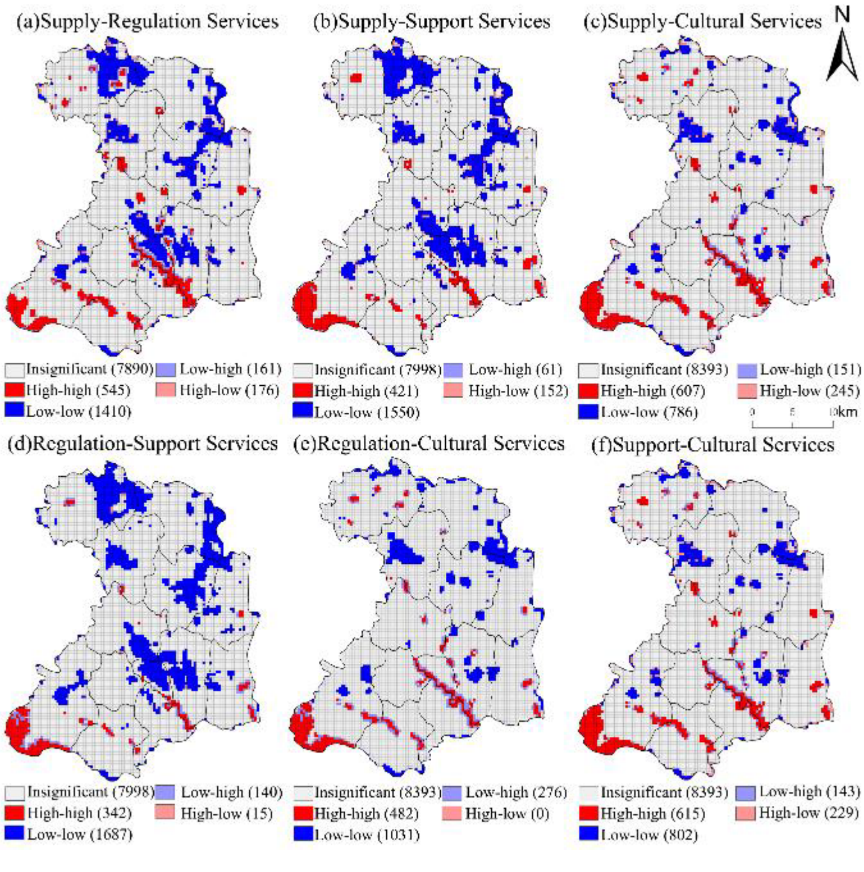

Figure 7. LISA map of four ESV functions under the cultivated land protection scenario in 2030

6. Research conclusions, discussions, and policy implications

We investigated the evolution features of territorial space and ESV in Xinzheng City spanning from 1980 to 2020, utilizing land use classification data derived from remote sensing images of Xinzheng City acquired at five different time points during the research period. Additionally, we simulated the multi-scenario evolution characteristics of ESV in 2030 using the PLUS model, revealing the tradeoffs and synergies. Based on our findings, we have drawn four key conclusions, initiated discussions to delve deeper into the research, and provided three policy suggestions.

6.1 Discussions

6.1.1 Predicting the spatiotemporal evolution of ESVs and tradeoff–synergistic relationships

Most of the current domestic studies concerning the spatiotemporal evolution of ESVs have summarized the spatiotemporal characteristics of ESVs based on existing data, such as land use change, with predictive studies in this regard being relatively scarce. Moreover, compared to similar previous studies [48], the present study comprehensively quantifies the interaction dynamics of the land system by considering socioeconomic, natural environment, and transportation factor changes in land use change prediction, and achieves a quantitative simulation of land system dynamics. This approach offers an innovative solution for simulating and assessing regional land system dynamics under different scenarios. In terms of spatial tradeoffs and synergies, our analysis reveals significant synergies among supply, regulation, and support services in Xinzheng City, indicating a mutually beneficial interaction among these components. In addition, the supply–culture services demonstrate a strong tradeoff relationship at the local level, indicating a competitive dynamic between supply services, dominated by agricultural production land, and culture services, dominated by ecological land. In the future, it will be crucial to consider the interests of these land types to effectively address ecological risks and ensure the ecological security of the region.

6.1.2 Recommendations for an urban development model based on ESV

As the urbanization process continues to advance, coupled with the insights gained from our multi-scenario simulations, it becomes evident that the spatial pattern of land in Xinzheng City will undergo substantial changes in the future. As one of the top 100 counties in China, Xinzheng City possesses a fragile ecosystem structure and is situated in a region with less favorable natural attributes. Consequently, the growing contradiction between humans and land is becoming increasingly pronounced. In the context of the national directives for "high-quality development" and Zhengzhou City's role as a "National Central City," the rational integration of ecological preservation and economic prosperity has become an unavoidable challenge in Xinzheng City's future development. From the perspective of ESV prediction and accounting, our study confirms that under the scenario of arable land protection, the development trajectory of Xinzheng City can be aligned with the stable supply of ESV, thereby eliminating risks to the latter. This scenario also underscores the potential for rapid economic development in Xinzheng City. However, agricultural land in Xinzheng City constitutes approximately 70% of the land type, and areas suitable for development and construction often overlap with the distribution area of high-quality arable land. This overlap presents a remarkable challenge, potentially leading to conflicts between urban infrastructure construction and arable land protection. Therefore, the urban development strategy for Xinzheng City should avoid urban sprawling patterns, prioritize arable land protection, and steadfastly adhere to the arable land preservation red line without wavering.

6.1.3 Shortcomings and prospects

Three limitations exist in this study due to constraints of length and data availability: 1) The land is classified into PLE land use types based on dominant functions; however, a notable challenge arises due to the overlapping functions observed among different land use types, rendering it complex to completely distinguish certain multifaceted PLE functional land types. 2) Given the constraints imposed by the limited computational capacity of the PLUS model, the selected model operates on a relatively large simulation scale. To enhance the precision and accuracy of multi-scenario future land use simulations in metropolitan suburbs, future research could explore alternative approaches such as employing artificial intelligence and other advanced modeling techniques to derive land use demands and spatial layouts. 3) The land use simulation did not consider the planning schemes of the Zhengzhou metropolitan area and other policy factors, potentially affecting the precision of land use simulation in Xinzheng City. Future research endeavors should prioritize the comprehensive consideration of government policy factors and the utilization of more detailed data sources. This approach will enable a comprehensive and accurate assessment of regional ESV over a long time and across multiple scales. Furthermore, it can unveil the internal driving mechanisms governing tradeoffs and synergies among ESV functions in metropolitan suburbs through advanced methodologies such as employing geographical detectors.

6.2 Research conclusions and policy implications

Using land use data for five time spans from 1980 to 2020 in Xinzheng City, the current paper employs PLUS model for simulating land use changes projected for 2030. Furthermore, we calculate the ESVs in Xinzheng City under different scenarios using the unit area equivalent method. The tradeoffs and synergies among ESV components are discussed using the spatial autocorrelation method, ultimately offering quantitative insights into how land use changes impact ESV across four distinct scenarios. The key conclusions are:

(1) Xinzheng City witnessed a rapid increase in industrial and mining production land and urban living land, whereas agricultural production land and ecological land for forest decreased remarkably. This trend of expansion of industrial and mining production land and urban living land was further accelerated by the ongoing construction of the Zhengzhou metropolitan area and Zhengzhou Xinzheng International Airport. Notably, industrial and mining

production land is estimated to experience a significant increase in area (36.15%) under the natural development scenario; moreover, agricultural production land will suffer the most significant reduction in area (3,055.36 hm^2) under the urban development scenario and witness the most substantial increase (959.24 hm^2) under the farmland protection scenario. Ecological land for pasture is projected to increase markedly under the ecological protection scenario. Consequently, Xinzheng City should prioritize the protection of agricultural production land to prevent a decline in the ecological benefits of both ecological land and agricultural production land. In addition, enhancing the ecological and cultural landscape values of agricultural production land, along with the development of specialty agricultural industries, can further bolster their ecological benefits.

(2) Between 1980 and 2020, Xinzheng City experienced a consistent decline in its total ESV, amounting to a remarkable reduction of 30.1 million dollars. During this research period, the functions of hydrological regulation and soil conservation accounted for a higher ESV proportion. Notably, the ESV of climate regulation, hydrological regulation, and soil witnessed the most substantial decreases. Low-ESV areas, which expanded continuously, are concentrated near the Zhengzhou Airport Economy Zone and Guodian Town Logistics Park. Conversely, high- and higher-ESV areas are distributed in the Shizu Mountain National Forest Park, Shuangji River, and major reservoirs, with the high-ESV areas in the north gradually disappearing after 1990. These findings underscore a notable trend of deteriorating ecological conditions in Xinzheng City. To address this, it is imperative to carefully plan the scale and spatial pattern of development in areas such as Longhu Town and the Airport Zone in the north of the study region, aligning them closely with the region's resource-carrying capacity and strict environmental capacity boundaries. This approach can collectively safeguard the overall ecological landscape and its associated benefits.

(3) Among all studied scenarios, the urban development scenario resulted in the lowest ESV, which was 1.68 million dollars less than that in 2020. Conversely, the cultivated land protection scenario yielded the highest ESV. Spatially, the change characteristics of ESV were consistent under the four scenarios, with the most significant decreases occurring in the main urban area, around the periphery of the Zhengzhou Airport Economy Zone, and at the junction of Mengzhuang Town, Xuedian Town, and Longwang Township. These findings emphasize that Xinzheng City can effectively maintain its ecological balance under the cultivated land protection scenario. In the future, efforts for ecological restoration in Xinzheng City should prioritize the cultivation and restoration of agricultural production land to safeguard its crucial crop production service function. In addition, strict measures to limit the encroachment of urban development on agricultural land must be implemented and the red line for arable land must be strictly adhered to.

(4) The tradeoffs and synergies revealed that all ESV functions in Xinzheng City exhibited consistent synergies under the four scenarios, with the cultivated land protection scenario demonstrating the most significant synergy. The synergy degree between regulation and supply services and support services was relatively high. Regarding spatial distribution, areas with high–high aggregation, such as the Shizu Mountain National Forest Park, Shuangji River, and reservoirs, as well as low–low aggregation areas, such as Zhengzhou Airport Economy Zone and Guodian Town Logistics Park, displayed significant synergies. However, the water system around the Shuangji River exhibited tradeoff characteristics. This underscores the effectiveness of the cultivated land protection scenario in maintaining the ecological balance of Xinzheng City. In the future, ecological management in Xinzheng City should prioritize the cultivation and restoration of agricultural production land to preserve its crucial crop production service function. Additionally, strict limit measures should be enforced to prevent the encroachment of urban construction land onto agricultural land and adhere steadfastly to the cropland red line.

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