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Delineation of Urban Growth Boundary Based on Habitat Quality and Carbon Storage: A Case Study of Weiyuan County in Gansu, China

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Abstract: As the impacts of climate change worsen, the global community prioritizes addressing it and fostering low-carbon societies. Urban planning focuses on creating compact, smart-growth cities that prioritize low-carbon, green development, with resource and environmental capacities as hard constraints. Balancing urban development, environmental protection, and accurate urban boundary delineation is vital for stable growth. In this study, the ecosystem services of Weiyuan County, Gansu Province, were assessed using the InVEST model's habitat quality and carbon storage modules. Key ecological protection areas with high biodiversity and carbon storage were identified. The CA-Markov model simulated urban expansion, dynamically coordinating ecological and urban development. Weiyuan County's habitat quality was mainly intermediate. In the county's central area, construction land coverage was 0.29 km^2 in the priority protection zone and 0.49 km^2 in the controlled development zone. Urban development boundaries in Weiyuan County were delineated based on ecosystem function rating and CA-Markov delineation. This method enhances urban management in ecologically fragile areas, promoting sustainable development and providing a reference for eco-economic sustainability in other fragile Chinese cities.

Keywords: habitat quality; carbon storage; CA-Markov model; sustainable development; urban development boundary

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1. Introduction

Since the 1950s, developing countries have witnessed unprecedented rapid urbanization [1,2]. China's urbanization rate, for instance, rose from 10.6% in 1949 to 63.89% in 2020 [3]. The UN-World Habitat's Cities Report (2020) forecasts that global urbanization will continue to grow over the next decade [4], with the urban population rising from 56.2% to 60.4% globally. Regional urbanization is expected to intensify, with 96% of urban growth concentrated in less developed regions, such as East Asia, South Asia, and Africa. India, China, and Nigeria are projected to contribute 35% of the world's urban population growth between 2018 and 2050.

In China, rapid urbanization primarily provides space for industrial development and population agglomeration. Urban land scale growth outpaces population urbanization, demonstrated by a 13.1% increase in urbanization rate and an 85% expansion in built-up areas from 2004 to 2014. Urbanization has resulted in extensive land occupation for construction and development, leading to land structure imbalances, urban sprawl, and negative ecological effects [5–7]. Addressing the relationship between urban development and ecological protection is a crucial issue in China's current state of urban planning [8,9].

Urban development boundaries, also known as urban growth boundaries (UGB), were first introduced by Howard's "Garden City" concept [10] and later replaced by "New Urbanism" [11] and "Smart Growth" theories, promoting mixed land use [12]. For instance, Rafiee et al. used the SLEUTH model to simulate urban growth for compact development in Mashhad city [13], while Chakraborti et al. applied an artificial neural network model to delineate hard and soft urban boundaries in Siliguri city [14], addressing ecological fragmentation in urban sprawl.

In 2013, the Central Committee of the Communist Party of China proposed a "spatial planning system" to delineate production, living, and ecological development control borders, aiming to strengthen land, natural resources, and ecological environment management and promote a harmonious human–nature relationship. Subsequently, the Central Urbanization Work Conference called for expedited delineation of development boundaries for all cities, especially mega-cities [15]. In 2014, the Ministry of Land and Resources and the Ministry of Housing and Construction collaborated to define urban development boundaries, selecting 14 key cities with populations over 5 million as pilot cities. The Central Committee and the State Council issued the "Provincial Spatial Planning Pilot Program" in 2017, proposing the demarcation of urban, agricultural, and ecological spaces, as well as permanent farmland and urban development boundaries.

Established in 2018, the Ministry of Natural Resources unified the exercise of "all national land space use control and ecological protection and restoration responsibilities". It conducted assessments of national land space development suitability, delineated control lines for ecological protection, as well as agricultural and urban development areas, and established a comprehensive national land use control system. The presidential speech at the 19th National Congress of the Communist Party also highlighted the importance of these lines for ecological preservation. The use of urban growth boundaries as a policy tool to limit cities' spatial expansion has become increasingly prominent. In this context, effectively responding to new territorial spatial planning requirements using advanced technical methods and exploring the scientific approach to urban growth boundary delineation have become essential for promoting the system's continuous improvement and smooth implementation [16–18].

UGBs have proven to be effective strategies for managing urban growth and mitigating the negative impacts of urban sprawl [19,20]. Consequently, they have been adopted in numerous countries, such as the US [21–23], UK [24], Saudi Arabia [25], Canada [26], Australia [27], Korea [28], and Germany [18]. However, Chinese cities are unique compared to those in other affluent countries due to their high population density and extensive sprawl driven by various environmental factors. Urban development boundary delineation practices in these countries can be classified into three main categories: controlling urban scale through green public space planning; emphasizing smart growth and policy control in the delineation process; and limiting urban sprawl through zoning control. Some Chinese researchers have applied growth boundary planning experiences from the United States, Europe, and other countries to investigate domestic growth boundary delineation techniques in China.

Long et al. developed the Beijing Construction Restricted Area Planning Support System (BJ-PSS), which combined a spatial database, a geographic information system (GIS), and professional planning models to support all technical aspects of boundary delineation [29]. It specified 110 construction restrictions as resistance factors to urban expansion and determined urban growth boundaries. Long et al. used a constrained cellular automaton model (CA) to demarcate city growth boundaries, taking into account various urban development factors [30]. Zhu et al. applied GIS technology to analyze and assess the ecological suitability of land in Fangchenggang City [31]. They delineated the construction space's rigid development and flexible expansion boundaries in the city's central area for rapid urbanization. The master plan delineated a strict development boundary beyond which no extension was planned, with flexible expansion occurring between the expansion border and the scaled boundary.

Two types of urban development boundary delineation exist. The forward delineation method focuses on urban development, describing the development boundary by predicting urban spatial development needs using geographic simulation models such as meta-cellular automata. The reverse delineation method focuses on constructing ecological security patterns, with the UGB delineated based on evaluation results obtained through ecological surveys or sensitivity evaluations [18,32,33].

While the above research provides theoretical and practical guidance for current urban development boundary delineation, some limitations exist in the practical application of delineation methods. For example, the ecological security pattern-oriented delineation method primarily evaluates single elements of biodiversity or habitat quality but does not consider natural factors and ecosystem services. Similarly, the two oriented research methods primarily consider either ecological security or urban expansion trends, with limited simultaneous consideration of both factors. Coordinating the relationship between quantities and controlling urban development boundaries is a critical issue that must be addressed and applied in China's spatial planning.

Weiyuan County, as the source of the Weihe River, the first major tributary of the Yellow River, faces the significant tasks of ecological restoration, soil and water conservation, and pollution control of the upper reaches of the Yellow River. However, it is also an economically depressed region, with a growing contradiction between urban development and ecological security. UGBs, essential for mitigating the increasing tension between urbanization and natural resource depletion, have been understudied in the economically backward area of the upper Yellow River. Moreover, coordinated ecological–urban development in this region is crucial not only for the sustainable development of the Yellow River basin but also for urban development in other ecologically fragile and economically disadvantaged regions. Based on this, this paper used Weiyuan County as the study area from a development and conservation coordination perspective.

First, we employed the InVEST model's habitat quality (HQ) and carbon storage and sequestration (CSS) modules to conduct a comprehensive assessment of the ecosystem services in the study area. We then delineated the primary target areas for ecological protection, which included areas with high-quality biodiversity and high carbon storage. Through territorial spatial planning, urban sprawl was effectively controlled, and regional economic, social development, and ecological protection goals were jointly achieved.

The urban expansion was simulated using the CA-Markov model, and the two results were spatially overlaid to define a growth boundary that balanced ecological protection with urban development.

2. Methods

2.1. Study Area and Data

2.1.1. Overview of the Study Area

According to the 19th Party Congress report, the major dilemma faced by China's society is the dichotomy between people's demand for an improved livelihood and imbalanced and insufficient growth [34]. With 1829 county-level administrative units in China and more than half of Chinese people producing and living in counties [35], the county level is where unequal and insufficient development is concentrated.

The county, as a relatively complete basic territorial unit of China's administrative and economic organizational activities, is a combination of China's macro- and micro-economies, a support point for urban and rural economic, social, and material construction exchanges, and has the characteristics of carrying on the city from above and the countryside from below in space. In China, county space is the primary carrier of small-town growth [36], carrying out critical functions such as transferring surplus labor, assembling township firms, maintaining rural stability, and serving as the primary battleground for poverty alleviation. County planning is a spatial planning strategy that focuses on the best allocation and development of county spatial features in a coordinated manner [15,37]. Considering rapid economic and socio-economic development fueled by accelerated urbanization, it is critical and necessary to conduct sound decision-making research on the long-term development of counties.

Weiyuan County is in Gansu Province's central region, with the coordinates 104°02′~104°49′ E and 33°26′~35°07′ N (Figure 1). The county has a total size of 2065 km^2. Weiyuan is the birthplace of the Weihe River, the Yellow River's largest tributary, and the crossing point for China's ancient Silk Road and Tangfan Road. With poor economic conditions and low output, the county is dominated by potato and Chinese herbal medicine planting. Previously, it was a prominent county in China's Liupan Mountain Area's poverty alleviation and development efforts. Furthermore, it is one of Gansu Province's 23 counties lifted out of poverty in February 2020. The northern part of Weiyuan is in the ecological function zone of soil and water conservation and dryland farming. The central part has similar features to the north, including biological production. The southern part is in the ecological function zone of water and biodiversity protection, based on the delineation of ecological function zones in Dingxi city.

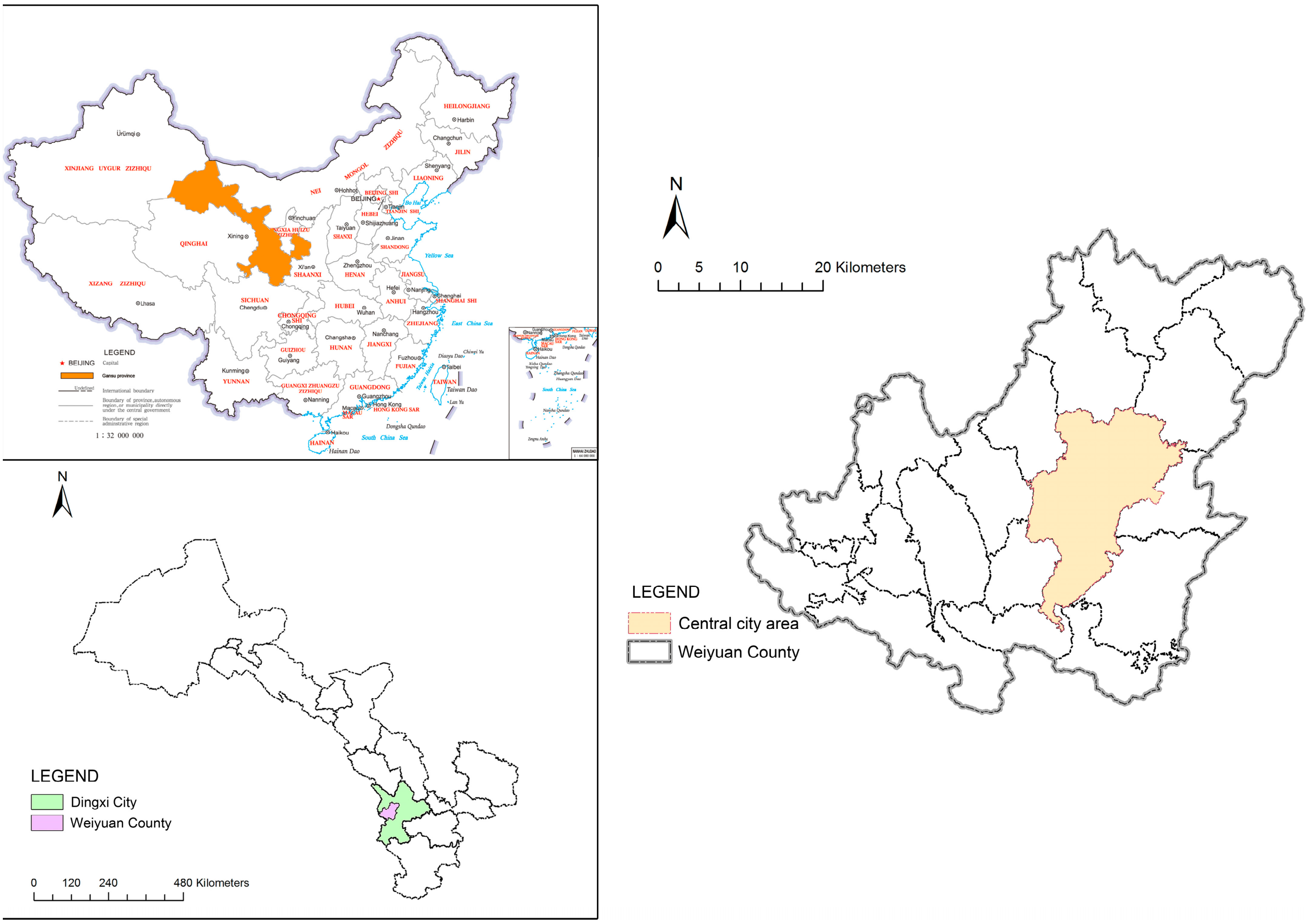

Figure 1. Topographic map of Weiyuan County.

The region is rich in ecological resources, with a poor economic foundation. Weiyuan County has been vigorously developing tourism, agriculture, and the Chinese herbal medicine processing industry, and constructing a good transportation system in recent years, as the poverty eradication plan continues. Urbanization is rapidly increasing, and urban expansion construction is evident, while the ecological environment faces more problems and consumes many natural resources. Preparing a new round of territorial spatial planning and the scientific and accurate delineation of urban areas is critical to maintaining the city's new status after being lifted out of poverty. This could also build a prosperous society that can effectively avoid reverting to poverty while ensuring the region's long-term ecological and social development and sustainability.

2.1.2. Data

Land use refers to humans' purposeful exploitation of land resources [38,39]. The land use data for 2010, 2015, and 2020 used in this paper were obtained from the Global Geo-information public product provided by the National Geomatics Center of China (http://www.globallandcover.com/ (accessed on 17 February 2022)). According to our research demand, Landsat image data were obtained using an object-oriented classification approach. The land was categorized into six key types depending on its use: grassland, forest, dryland, urban building, water, and unused land. The data resolution was 30 m $\times$ 30 m.

2.2. Habitat Quality and Carbon Stock Assessment Models

Bagstad et al. used habitat quality and carbon stock assessment models to evaluate the efficacy of 17 ecosystem service tools using eight assessment criteria [40]. However, the integrated valuing of ecosystem services and tradeoffs (InVEST) model is the most developed and extensively used ecosystem service evaluation model among the many available [41–43]. The U.S. Natural Capital Project Team created the InVEST model to measure ecosystem service functions and their economic worth to aid ecosystem management and decision making. The InVEST model includes quantitative and projection models and three ecosystem service assessment models—terrestrial, freshwater, and marine. The models can simulate changes in ecosystem service functions under land use and cover change scenarios, thus providing a scientific basis for ecosystem management and policy development.

China has experienced rapid urbanization, and with ongoing economic development and population concentration, the area of urban construction land has increased quickly. This has created a number of issues, including the loss of high-quality arable land surrounding cities and the devastation of the natural environment [44]. The Chinese government recommended the UGB demarcation to solve these issues. Delineating urban land in China should therefore guarantee the regularity of the spatial and temporal patterns of urban development while also fulfilling the needs of the ecosystem services. Additionally, the most essential component of ecosystem services is biodiversity, which is represented by habitat quality. In order to strike a balance between human development and climate change, low-carbon city development must be considered. The Chinese government informed the world community in September 2020 that it will boost its national contribution, enact tougher laws and regulations, and work toward reaching carbon neutrality by 2060 in order to meet peak CO_2 emissions by 2030. In order to lessen the effect of urban expansion on climate change and to as quickly as possible meet China's "peak and neutral" carbon targets, this study will conduct both carbon stock and sequestration analyses.

We assessed habitat quality and carbon storage in the study area using two modules of the InVEST model 3.2.0 (i.e., habitat quality and carbon storage and sequestration).

2.2.1. Habitat Quality Evaluation

Habitat quality is the environment's ability to provide populations with the conditions for long-term survival. It is based on the availability of subsistence supplies, and the ecosystem's ability to reproduce, exist, and offer conditions suitable for populations and individuals [45–47]. In general, increased land use intensity in the vicinity is seen as a cause of habitat degradation [48–50]. Areas with high habitat quality promote biodiversity, and those with low habitat quality support lower biodiversity persistence, resilience, and recovery.

We used habitat quality to assess the overlap and compromise between ecosystem service delivery, biodiversity conservation, and land use practices. The scoring criteria, habitat quality level, and grade features are shown in Table 1. The HQ module works mainly by assessing the extent of the degradation of a habitat or vegetation type to reflect habitat quality and scarcity. Four main factors influence the degree of degradation: the associated effect of each threat, the associated risk of each habitat, the spacing between the grid cell and the threat, and the degree to which the unit is legally safeguarded [51]. The model posits that a habitat type with a higher vulnerability to a threat is more likely to be degraded by the threat. As a result, the severity of a habitat unit's total vulnerability level was utilized to examine the degree of degradation of the habitat unit. The following is the model specification for the total threat level for grid x in each habitat type j.

$$D_{xj} = \sum_{r=1}^{R} \sum_{y=1}^{Y_r} \left(\omega_r / \sum_{r=1}^{R} \omega_r \right) r_y i_{rxy} \beta_x S_{jr}$$

where r is the threat factor and R denotes the total number of threat factors across all categories; y denotes a raster in threat factor r, and Y_r denotes the total number of rasters occupied by threat factor r; i_{rxy} is the decreasing rate of the distance of the impact of threat r in raster y on raster x habitats; x is the accessibility of habitat raster x; r is the relative destructiveness of threat factor r to all habitats; r_y is the intensity of threat factor; i_{rxy} is the decreasing rate of the distance of the impact of threat r in raster y on raster x habitats; and S_{jr} denotes the sensitivity of habitat type j to threat factor r. The formula is as follows, where i_{rxy} has two forms of decay, linear and exponential:

$$\left. \begin{array}{r} i_{rxy} = 1 - \frac{d_{xy}}{d_{r\ max}} \\ i_{rxy} = exp\left(-2.99 d_{xy} / d_{r\ max}\right) \end{array} \right\}$$

where d_{xy} is the linear distance between raster x and y, and $d_{r\ max}$ is the maximum impact of the distance of threat r. The expression of habitat quality for patch group x in habitat type j is as follows:

$$Q_{xj} = H_j \left[1 - D_{xj}^z / \left(D_{xj}^z + k^z \right) \right]$$

where H_j is the habitat suitability of land cover type j; D_{xj} is the degree of habitat degradation; k is the half-saturation parameter usually taken as half the maximum value of D_{xj} after the model trial run; and z is the normalization constant, taken as 2.5 according to the InVEST model user guide.

Based on the ecological threat source classification criteria in the InVEST 3.2.0 platform and a review of the relevant literature, sites with high human disturbance were selected as threat sources [49]. This study uses the results of the expert survey method reported in earlier studies to assign values to the impact range of threat sources and their weights [52–55]. It also refers to existing InVest model applications in selecting arable land, rural settlements, urban land, and major traffic arteries (e.g., national and provincial highways) as threat sources (Table 1).

Table 1. The impact range of threat sources and their weights.

Threat Source	Impact Range/km	Weighting	Decay Type
Cropland	8	0.7	L
Rural settlements	5	0.6	L
Urban land	10	1.0	L
Main traffic arteries	3	1.0	E

Each habitat type has a different level of sensitivity to threats. Alkemade et al. used expert opinion to assess the relative mean species abundance of each land class in the GLC2000 (global land cover) as an index to define biodiversity in their research of global terrestrial biodiversity change [56]. Other studies used the InVEST model to assess habitat quality and acquired the sensitivity of habitat suitability and threats using the expert survey approach [52,53]. Gao et al. ranked the various habitat categories from highest to lowest in terms of sensitivity as follows: saline land > wetland marsh > river, woodland > grassland > cropland. Here, we refer to the findings from previous studies on ecological sensitivity in

China and overseas and expert advice to determine habitat suitability and sensitivity to threats.

2.2.2. Carbon Storage and Sequestration Assessment

At the 75th United Nations General Assembly session on 22 September 2020, in New York, President Xi Jinping stated that China will enhance its independent national contribution, adopt stronger measures and policies, and realize peak CO_2 emissions by 2030 and carbon neutrality by 2060. Changes in land use patterns and land cover types around cities have occurred as urbanization has accelerated, with implications for carbon storage in terrestrial ecosystems. We used the carbon storage and sequestration level of the InVEST model to assess carbon stocks in the study area. Areas with high ecosystem regulating services were identified, boosting greenhouse gas uptake and sequestering carbon dioxide. The societal value of the increased sequestered carbon is similar to preventing carbon release into the atmosphere due to anthropogenic causes [57]. This is critical for China to reach its carbon neutrality and carbon peaking targets.

In the InVEST model, the carbon module of the terrestrial ecosystem is based on the land use type map, and the carbon density of the four-carbon pools corresponds to different land types and wood felling rates. This was used to calculate the current carbon sequestration, the sequestration in different places, and the dynamic change in carbon storage over a specified period. The four major carbon pools of the ecosystem are aboveground biomass, belowground biomass, soil, and dead organic matter. The total carbon storage is the sum of vegetation carbon storage and soil carbon storage.

Carbon stock must be estimated to set the carbon density for different land cover types. Several studies have measured carbon density in China [58–62]. Many factors influence vegetation carbon density, including temperature and precipitation. The more favorable the combination of water and heat factors for plant growth, the higher the plant biomass and vegetation carbon density [63].

To estimate the carbon stock of Wu'an City, Huang chose two representative factors, air temperature and precipitation [64]. The authors calculated the correction coefficient of precipitation on carbon density using the formula developed by Alam et al. and the correction coefficient of air temperature on carbon density using the formula developed by Chen et al. [42,65]. Subsequently, the carbon density data were corrected at the national level. In this study, the average annual temperature and precipitation of Weiyuan County were used to correct the carbon density parameters of Weiyuan County (Table 2), based on the carbon density summary of different land cover types reported in the studies above.

Table 2. Carbon density of land use components in Weiyuan County (t/hm^2).

Land Use Type	C_{above}	C_{below}	C_{soil}	C_{dead}
Cultivated land	5.7	80.7	108.4	13
Forest	42.4	115.9	236.9	13
Grassland	35.3	86.5	99.9	2
Water	0	0	0	0
Construction land	1.2	0	0	0
Unused land	9.1	0	21.6	0

The land use and carbon pool data were entered into the InVEST model for carbon storage and sequestration activities. The total carbon sequestered under different land types was calculated based on the current land use type. The ensuing results were overlaid with habitat quality assessment results to determine the priority conservation areas. This was aimed at simultaneously reducing the impact of urban development on climate change and achieving the goal of "carbon peaking and carbon neutrality" in China.

2.3. Urban Sprawl Simulation Using CA-Markov Model

The Markov chain analysis algorithm and the meta-cellular automata analysis algorithm are the major methods employed in this study to simulate urban sprawl modeling. We used a transfer probability matrix to describe changes in land use over time. Markov chain analysis is a traditional modeling method for land use changes based on the Markov process. It analyzes the changing trend between objects using preliminary state and transfer probabilities [66]. The Markov analysis model simulates the land use state using the transfer probability matrix P between different periods and types of land depending on the existing land use state. The following is the initial probability transfer matrix:

$$\begin{bmatrix} P_{11} & \cdots & P_{1n} \\ \vdots & \ddots & \vdots \\ P_{n1} & \cdots & P_{nn} \end{bmatrix}$$

where n is the number of land use types, P_{ij} is the probability of converting type i land to type j land, and P_{ij} satisfies two conditions: ① $0 \leq P_{ij} \leq 1$; ② $\sum P_{ij} = 1$ (i, j = 1, 2, 3, . . . , n). Given that the results of Markov analysis lack a spatial component and land use change is a spatialized process [67], a CA model with a spatial analysis function is required. This model uses a "top-down" approach and is defined by discrete spatio-temporal states. The CA model primarily depicts local interactions in the system's evolutionary dynamics and may simulate stochastic, nonlinear, and geographic trends. Each cell's state changes under the neighborhood state and transition rules. The CA model has been demonstrated to simulate complicated processes in land use and urban systems [68]. The following is a description of the model:

$$S(t, t+1) = f[St, N]$$

where S is the tuple's set of finite discrete states, f is the tuple's transition rule function, N is the tuple's neighborhood, and t and $t + 1$ are two separate moments. The CA-Markov model combines the benefits of long-term predictive simulation and spatial variation simulation of the CA model, allowing it to better predict and simulate the spatio-temporal pattern of LUCC in quantity and space. S is the set of finite discrete states of the tuple, f is the transition rule function of the tuple states, N is the neighborhood of each tuple, and t and $t + 1$ are two different moments.

The CA-Markov model was tested using the point-by-point comparison approach to calculate the kappa index for small study areas. Cohen (1986) proposed the kappa index, implemented in IDRISI's CrossTab module in this study. Its calculation principle is as follows:

$$\text{Kappa} = \frac{p_0 - p_c}{1 - p_c}$$

$$p_0 = \frac{s}{n}$$

$$p_c = \frac{(a_1 \times b_1 + a_2 \times b_2)}{n \times n}$$

where n is the total number of raster pixels; a_1 denotes the number of pixels of the real raster for construction land; a_2 denotes the number of pixels for non-construction land; b_1 is the number of simulated raster pixels for construction land; b_2 denotes the number of pixels for non-construction land; and s is the number of pixels in the real and simulated rasters with equal values of corresponding pixels. When the kappa coefficient exceeds 0.6, the model simulates the land use type with high spatial accuracy and a good simulation effect.

The simulation prediction results in 2020 were combined with the actual decoded 2020 land use data for comparison and analysis in this study using IDRISI software. The estimated kappa index was 0.77, a satisfactory simulation effect that meets our research needs. Therefore, this model can be used to project land use in 2035.

3. Results and Discussion

3.1. Habitat Quality and Carbon Stock Overlay

3.1.1. Habitat Quality Evaluation

The relevant base map and parameter data were imported into the HQ module of InVEST software and executed to generate the Weiyuan County habitat quality evaluation grid, with the evaluation results separated into four grades: poor (0–0.1), medium (0.1–0.4), good (0.4–0.6), and excellent (0.6–1.0). The results are shown in Figure 2. The habitat suitability and the corresponding relative sensitivity to different threat sources and their parameter values are listed below (Table 3). The habitat quality grade in Weiyuan County is primarily medium. The areas with good HQ are concentrated in southern Weiyuan County, part of the western extension of the Qinling Mountains, with dense vegetation and three major forest farms, namely Huichuan, Wuzhu, and Lianfeng, which must be protected from development. Construction land in the central city, village, and town settlements had poor habitat quality.

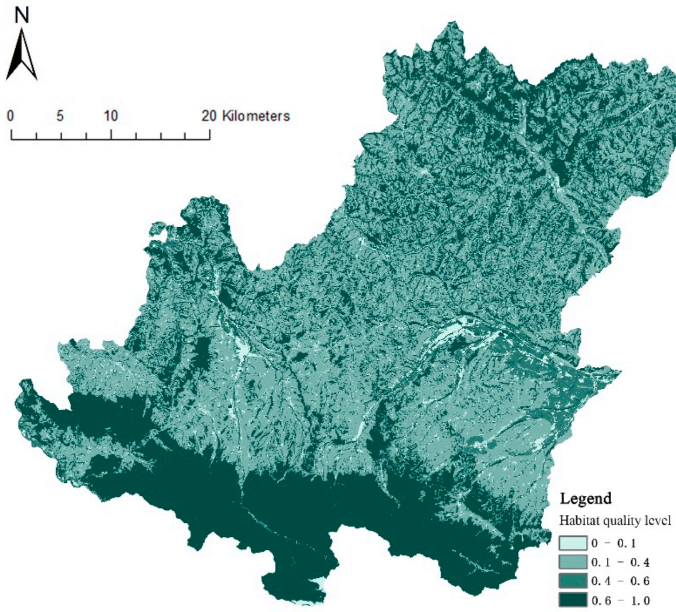

Figure 2. Habitat quality evaluation results grading chart for Weiyuan County in 2020.

Table 3. Habitat quality evaluation results grading.

Score Criteria	Habitat Quality Level	Grade Features
0~0.1	poor	Severe degradation or loss of ecosystem structure and function to meet ecosystem development requirements
0.1~0.4	medium	Ecosystem function is degraded, and ecosystem structure has changed largely and is insufficient to support ecosystem needs
0.4~0.6	good	High vegetation cover, good ecosystem service functions, more stable structure, suitable for regional ecosystem development
0.6~1.0	excellent	Biomes with dense populations, a stable ecosystem structure, and services conducive to sustainable ecosystem development.

3.1.2. Carbon Storage and Sequestration Assessment

The InVEST model provides a raster map of the distribution of carbon stock values for different carbon quantities while predicting the county's carbon stock (Figure 3). As shown in the graph, the highest carbon storage value in the grid of Weiyuan County in 2020 was 36.738 kg, concentrated in the southern area, particularly in the distribution region where forest land is located. Due to large vegetation in the area, the carbon content of the vegetation soil is three times that of the above-ground biomass and two times that of the atmosphere [69,70], making it the largest source for total carbon storage and having a relatively high carbon storage capacity. Construction land and water are the most common land categories in low-value areas.

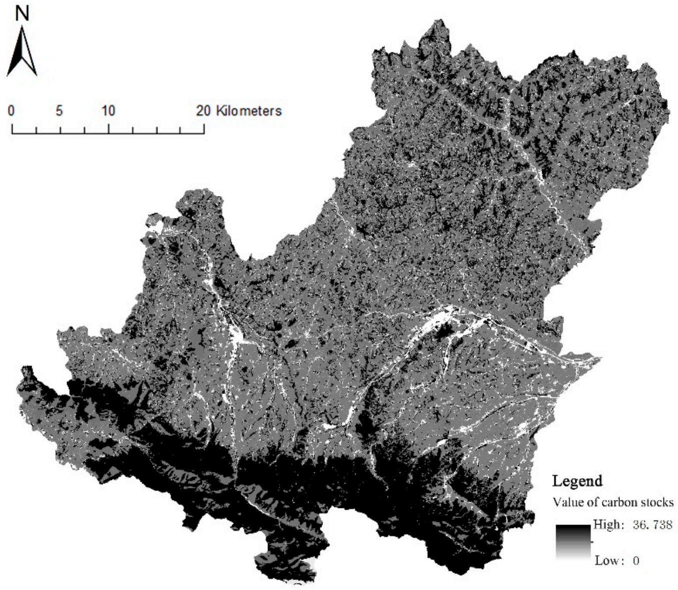

Figure 3. Distribution of carbon stocks in Weiyuan County in 2020.

3.1.3. Habitat Quality Assessment Overlaid with Carbon Storage and Sequestration Assessment

The InVEST model demonstrates that biodiversity, an ecosystem support service, is characterized by habitat quality, whereas carbon sequestration regulates ecosystems. The assessment results must be normalized to the same interval, and the relevant weights computed to superimpose the two spatially. Cui combined expert advice with terrestrial ecosystem service evaluation index and assigned 0.7 and 0.3 for habitat quality and carbon storage, respectively, to measure the integrated level of ecosystem services [71]. This study created the raster for the integrated evaluation of habitat quality and carbon storage services by weighting habitat quality and carbon storage and sequestration models, with values ranging from 0.03 to 11.72. Using the natural discontinuity classification approach, grading according to the law of the statistical distribution of values to maximize the difference between classes [72], the raster data were grouped into low (0–4), medium (4–8), and high (8–12) (Figure 4 and Table 4).

Table 4. Comprehensive ecosystem service grading and the corresponding area in Weiyuan County.

Comprehensive Grade of Ecosystem Services in Weiyuan County	Area (km^2)	Percentage (%)
Low (0–4)	148.33	7.22
Medium (4–8)	1281.81	62.42
High (8–12)	623.45	30.36
Total	2053.59	100

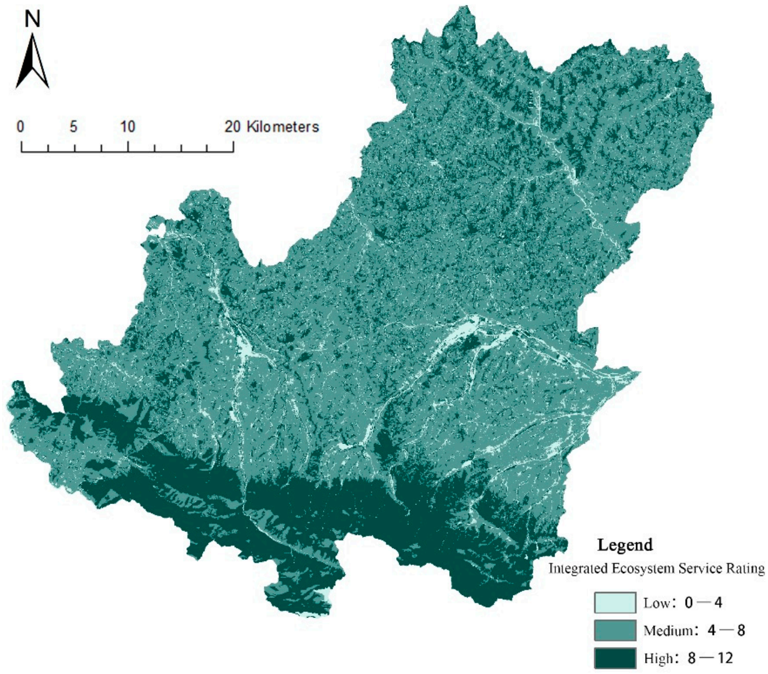

Figure 4. Results of the comprehensive evaluation of ecosystem services in Weiyuan County in 2020.

From Figure 3 and Table 4 above, it can be seen that 30.36% of the land in Weiyuan County belongs to the area with a high ecosystem service level, with forest land as the main land use type. In total, 62.42% belongs to the area with "medium" ecosystem service level, with arable land as the main land use type; only 7.22% belong to the area with "low" ecosystem service level, with urban construction as the main land use type. A total of 7.22% of the land area has a "poor" ecosystem service level, with urban building as the most common land use type.

Regarding the actual development of Weiyuan County and the ecological conservation and non-development plan, the region with a "high" ecosystem service level is defined as a priority protection area for future development (i.e., a prohibited development area). Controlled development areas are defined as areas with a "medium" level of ecosystem services, and suitable development areas are locations with a "low" level of ecosystem services.

3.2. Markov Model Results

Land use data for 2010 were simulated using the CA-Markov model, and the simulation results were compared with the actual land use in the same year. The Kappa coefficient of accuracy test was 0.77, indicating that the model's reliability is excellent. The simulation results were close to those of the real-world situation, and the simulation effect was good. Therefore, the model can simulate and predict land use in 2035, as shown in Figure 5.

3.3. Urban Development Boundary Delineation

By overlaying the simulated construction land with the zonal ecosystem service data, we found that the simulated construction land in Weiyuan County's central urban area exceeded the ecosystem service evaluation's suitable development area. The simulated construction land also expanded to the controlled development area and priority protection area, and spatial decisions were made to adjust the conflicting map spots in conjunction with the actual land use in Weiyuan County [73,74]. The area of construction land in the priority protection area obtained from the simulation was 0.29 km^2, and the coordination principle was to prioritize the protection of the ecological environment. Thus, these construction sites can be moved out from the control development area and retained as lands for the ecological environment.

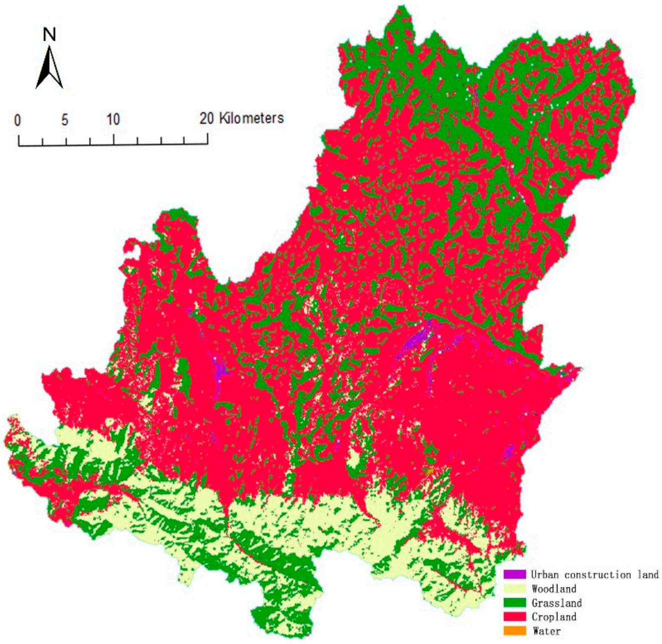

Figure 5. The construction land was taken from the rasterized simulation results in ArcGIS, where the scale of urban construction land in Weiyuan County's central city in 2035 is 6.67 km^2.

The construction land in the control development zone covers 0.49 km^2, as predicted by the Markov model. Since the coordination principle focuses on urban and regional development, these sites should be moved out of the control development zone and kept as construction land. The construction land in the priority protection zone should be reserved for eco-friendly use. The centralized contiguous construction land boundary of the central urban area of Weiyuan County in 2035 was extracted after setting the area threshold for the adjusted urban construction land scale. The comprehensive mapping formed the central Weiyuan City's urban development boundary (Figure 6).

3.4. Discussion

3.4.1. Comparison with Existing Research

Today's urban management challenges involve balancing urban development with ecological protection goals. The ecological red line, permanent basic agricultural land, and urban development boundary are key elements of China's new round of spatial planning, promoting sustainable and balanced economic and environmental development [75–77]. The results of urban development boundary delineation achieved by integrating ecosystem service evaluation and urban expansion simulation align with the future spatial development pattern of Weiyuan County, showcasing the protection of high-quality ecological land while meeting the county's sustainable economic and social development needs. Our findings demonstrate that combining the CA-Markov and InVEST models provides an effective basis for curbing urban sprawl [32,76], optimizing land use structure [64], and guiding rational urban growth.

This study demonstrates that the InVEST model is methodologically feasible and scientifically sound. It represents a useful exploratory attempt to identify ecological priority conservation areas and delineate rigid urban development boundaries [40,43,72]. We found that the area with the highest HQ grade was in the mountainous part of the study area, extending to the Qinling Mountains, with woodland as the primary land use type. The ecosystem in this area has a greater potential to provide the necessary conditions for individuals, populations, or communities to survive and reproduce. Moreover, the high-quality habitat area also reflects the resistance of each patch in the habitat to degradation caused by anthropogenic factors [38,78,79], including weaker land development and utilization intensity. The lower habitat quality area was characterized by a high percentage of construction land, consistent with the findings of Hao et al. [80].

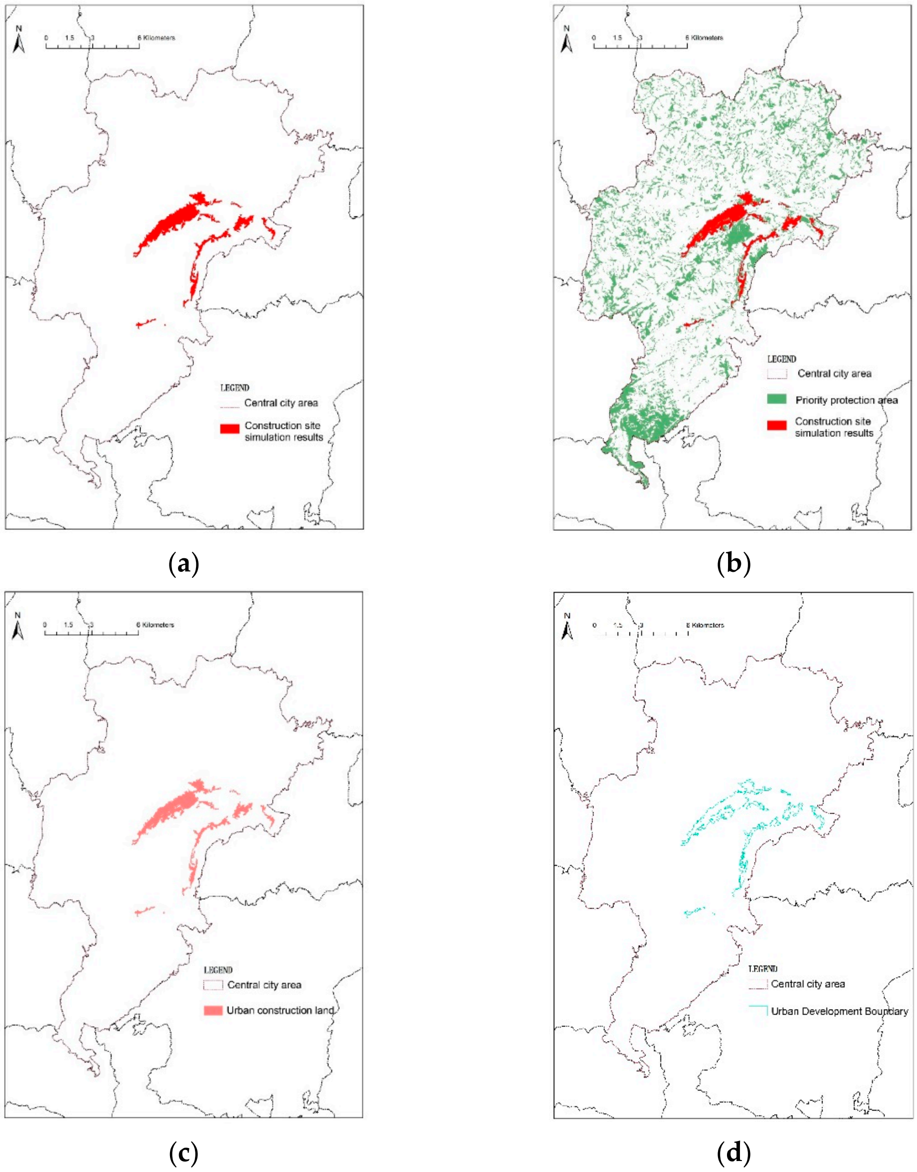

Figure 6. The 2035 Urban Development Boundary in the Central City of Weiyuan County. (**a**) Simulation results of construction land expansion; (**b**) ecosystem services priority conservation areas intersect with expansion simulation results; (**c**) the scope of construction land after transferring out of the priority protection zone; and (**d**) extracting boundary contours.

In this study, the simulation is improved by combining the decoded real 2020 land use data with the Markov projected 2020 land use data. As a result, the simulation of land growth in 2030 has a high degree of spatial accuracy. Numerous studies have examined the viability and applicability of the Markov chain model, finding that its predictions are highly accurate when compared to actual outcomes [81–84].

Our spatial decision analysis of ecological sensitivity evaluation and urban expansion simulation results differs from earlier reports [32,85]. Our findings reveal that ecological sensitivity evaluation and urban expansion simulation are two separate processes. When layout conflicts occur, the dynamic adjustment of both can be achieved, emphasizing the synergy between urban development and ecological protection.

3.4.2. Research Limitations

Despite the scientific approach and comprehensive evaluation of ecosystem services using the habitat quality and carbon stock modules of the InVEST model, this study has some limitations. One such limitation is that biodiversity, the most fundamental component of ecosystem services, is represented only by habitat quality. Carbon stock and CO_2-driven climate change are closely related, and both biodiversity loss and climate change are significant challenges facing ecosystems during urbanization.

Ecosystem services are a mega-complex system, and no study can possibly take into account all pertinent variables. Future research should take into account as many affecting elements as feasible when they are known.

4. Conclusions and Policy Implications

Starting from the relationship between urban development and environmental protection, this paper assesses the role of ecosystem services using habitat quality and carbon storage, delineates ecological priority protection areas, simulates urban expansion with the CA-Markov model, and finally delineates the rigid urban development boundary at the end of the new round of territorial spatial planning (2035) in a dynamic and coordinated manner. We find that by combining the spatial coordination mechanism of ecosystem service evaluation and urban expansion simulation, the delineated urban growth boundary (UGB) conforms to the planning trend for expanding the central urban area of Weiyuan County. Similarly, due to the consideration of ecological quality, the scope of the UGB not only restrains blind urban development but also protects the ecological and agricultural space in the region. While prioritizing the protection of ecological land, it also satisfies the sustainable economic and social development of Weiyuan County, providing a basis for effectively restraining urban sprawl and guiding rational urban development. This has a relevant and valuable application in the new round of territorial spatial planning in Weiyuan County.

Weiyuan is an ideal case study to evaluate the efficacy and applicability of the novel design approach since it has a diverse range of landforms, ecosystems, and land use types. The implications from this research are as follows: (1) The model determines the urban development scale based on the idea of “implementing the protection boundary first, then the development boundary”. In delineating urban development boundaries in areas with rapid urban development but a relatively weak ecological environment, the government can permanently protect the ecological core resources such as rivers and lakes, forest parks, water reserves, and other important resource spaces as ecological protection red lines in the planning of areas with “high” ecosystem service levels. On this basis, urban development boundaries can be defined to reflect not only the function and structure of the city, but also the interaction between the city and the natural environment in which it is located. (2) Strengthening stock development and redevelopment after the urban development boundary is demarcated to form a virtuous land development cycle. The UGB is an effective means and management tool to promote urban development and transformation. On the one hand, the implementation of UGB can control urban sprawl and promote intensive land use; on the other hand, the pressure of urban expansion can be indirectly relieved by tapping the internal potential of towns, which is a kind of protection for the delineated urban growth boundary. For example, the regional planning of old urban areas can be updated to improve their accessibility, which can not only effectively improve urban functions, but also reduce the pressure on agricultural and ecological land around the city. In this sense, the application of our proposed UGB delineation framework in a rapidly growing city in China proves the applicability and reliability of the framework, and this approach to town development boundary delineation thus has implications for urban growth management in other developing countries that face conflicting development and conservation. This approach can be an interesting tool for spatial science, planners, and managers. A possible application area is the analysis of urban land use patterns and their changes to support urban planning.

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