



Article

Constructing Landscape Ecological Security Patterns of an Ancient Capital Based on Cellular Automata Theory

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Abstract: Urban sprawl in developing countries changes urban land use structure and function, and threatens the sustainable development of regional ecology and security patterns of city landscapes. A new way to control urban sprawl is to develop a comprehensive landscape security plan, analyze factors influencing urban growth, optimize land use and demarcate a growth boundary. Here, we use Xi'an, China, as a case study to analyze scenarios of landscape security pattern and urban spatial control to explore urban spatial zoning. We construct a theoretical framework of a landscape security pattern to manage urban spatial expansion from the perspective of landscape security and urban smart growth. As a first step, the integrated landscape security pattern is constructed based on four factors: hydrology, geological disasters, cultural heritage, and recreation. Second, the urban spatial expansion model is simulated based on a cellular automata model. Finally, nine land-use patterns are developed by overlaying integrated landscape security patterns and urban spatial expansion. Thus, urban space is divided into three types of zoning scenarios: suitable construction, restricted construction, and prohibited construction. The calculations indicate that the zoning area of the three types accounted for 10.4%, 14.7%, and 74.9%, respectively, of the total area in Xi'an. It is of great significance to determine the spatial contradiction between development and protection in the process of urban expansion and to establish a schema of suitable urban land use. We discuss the rapid urbanization process in developing countries at the macro scale, and formulate a land use plan that balances development and protection.

Keywords: landscape security pattern; urban spatial expansion; spatial zoning scenario; Xi'an



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1. Introduction

Since 1978, rapid urbanization in China, a phenomenon stimulated by economic and social reform, has not only driven urban economic development but also caused Chinese cities to expand at an unprecedented speed and scale. The growth rate of developed land area has increased with the growth of the urban population, but changes in the structure and function of urban land use threaten the sustainability of regional ecology and landscape security pattern in urban areas [1–3]. With the expansion of cities, landscape security for the provision of water, cultural heritage, and cultivated land are becoming increasingly prominent. For example, rapid urbanization in the Middle East challenges urban water security [4]. High-intensity development and construction, especially of networks of regional infrastructure, have brought clear negative externalities to urban areas [5]. Due to the absence of regional planning, guidance, and the lack of foresight in the development of cultivated land, there has been increasing fragmentation of agricultural land—a serious threat to food security [6]. Rapid urbanization has intensified conflicts

among identified functions in urban space [7], creating a serious threat to the core interests of urban development and exposing a need to control urban space [8]. The study of urban spatial expansion in relation to landscape security patterns has become a topic of great interest to the interdisciplinary research field of landscape ecology and urban and rural planning [9], especially with regard to landscape security and smart city growth complementary through spatial regulation, representing a new research area [10,11].

As a land management policy based on spatial differentiation, spatial regulation plays an important role in protecting natural area ecology, limiting urban sprawl, and exploring sustainable economic and social development [12]. Currently, the primary tools of urban space regulation include construction land control, open space preservation, space policy guidance, urban growth boundaries, and spatial zone control [13]. Controlled zoning refers to government decision making as the main tool of urban space regulation, including construction and management regulation to control public resources, coordinate space development and protection, and realize the sustainable use of urban space resources [13].

The existing spatial zoning model has shortcomings: application limitations, factor imbalance, and a lack of comprehensive zoning [14]. Land development suitability evaluation is the usual method of delimiting urban spatial control zones. However, this zoning scheme, which pays inordinate attention to the degree of suitable construction and development quality of land, tends to ignore landscape safety protection [15]. Therefore, for national resource planning in many countries, it is not reasonable to consider environmental carrying capacity as a key constraint in attempts to solve problems of uncontrolled urban expansion caused by rapid development [16]. National resource planning should be based on an analysis of the location and connectivity (fragmentation) of important landscape elements [17], taking into consideration the control and positive growth of urban sprawl through the construction of regional landscape patterns [18–20].

However, anti-planning theory overemphasizes the protection of non-construction area (landscape safety factor), resulting in it being questioned based on its lesser consideration of urban spatial expansion [21]. In recent years, based on reflections of land development suitability evaluation and anti-planning theory, research into the security pattern of multi-factor landscapes in urban spatial expansion has achieved fruitful results. Urban growth simulations can assess and predict the potential outcomes among policy scenarios and assist in urban and regional planning decisions [22]. A new way to control urban sprawl has been to construct comprehensive landscape security patterns, analyze the influencing factors of this growth, and develop land optimization strategies [23,24], thus guiding the development of urban health [25,26]. This permits the demarcation of urban growth boundaries based on the simulation of urban construction land expansion [27]. However, existing research has not clearly addressed the landscape security scenario model of urban spatial expansion, which inevitably creates the dilemma of a single perspective: landscape security or intelligent urban growth. Therefore, in this paper, we aim to construct a theoretical framework of landscape security patterns to explore urban spatial expansion from the perspective of landscape security and intelligent urban growth.

We use the city of Xi'an as an example, analyzing the scenario pattern of landscape security patterns and urban spatial control zones using the following steps. First, the theoretical framework of urban spatial control zoning is developed based on the simulation of landscape security patterns and urban spatial expansion. Then, compared to a baseline situation and data analysis of Xi'an, the results of the comprehensive landscape security pattern, urban space expansion, and urban space control zoning of Xi'an are analyzed.

2. Materials and Methods

2.1. Integrated Landscape Security Pattern

Using landscape ecology theory, important landscape elements selected for this study included comprehensive water, geological hazard protection, cultural heritage, and recreational entertainment (Figure 1). Among them, comprehensive water (water resources, water hazards) includes rivers, lakes, and water conservation areas. Geological hazard pro-

tection includes debris flow, landslides, and collapses. Cultural heritage includes ancient sites and ancient tombs. Finally, recreational entertainment includes scenic spots, urban parks, animal, recreational buildings, plant gardens, etc.

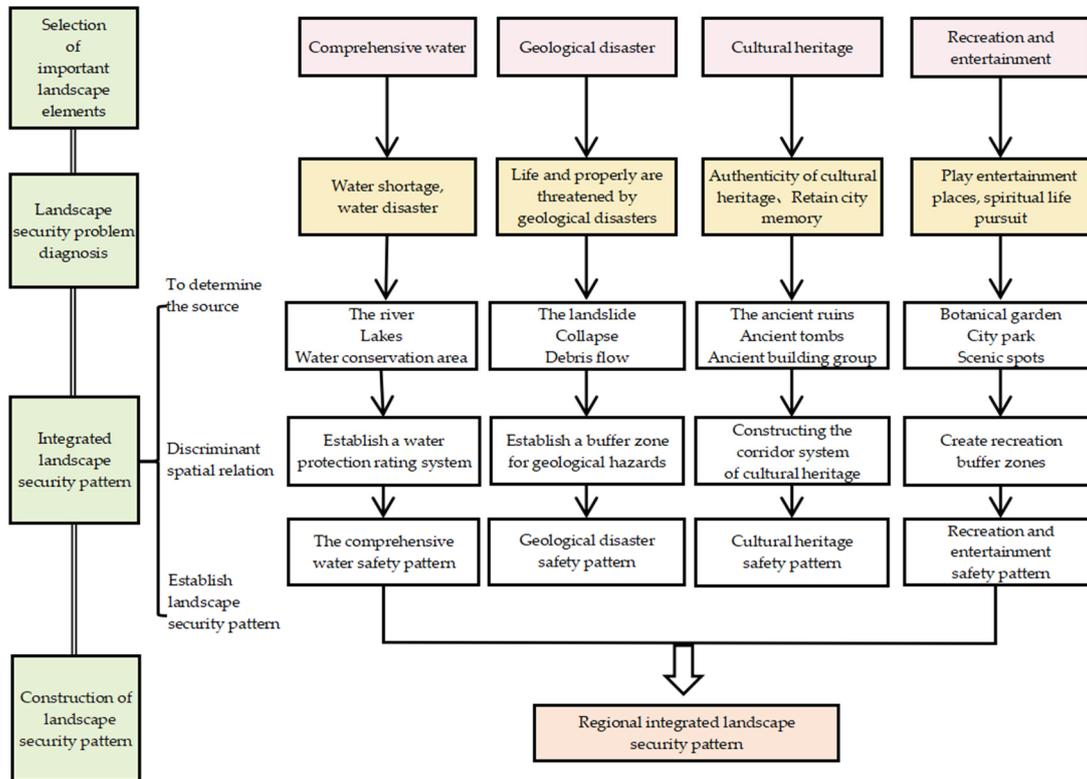


Figure 1. Construction framework of integrated landscape security pattern.

The first step is to determine sources of regional landscape services. Sources should possess internal homogeneity and the ability to gather or diverge towards the “source” itself. A source is the starting point for the distribution of landscape elements and the foundation of expansion. Within a particular study area, the “source” is generally considered to be an area where the ecosystem is relatively stable [10]. Whether a certain landscape element can be used as a “source” is largely determined by the spatial distribution and suitability analysis of the resources according to the characteristics of the landscape in the study area.

The next step is to determine buffer zones. Buffer zoning is usually represented by a resistance surface. The influence of landscape elements on the surrounding environment is regarded as the process of assimilation. The cover of spatial resources around the landscape elements, and the assimilation and cover of the surrounding spatial resources must be realized by overcoming landscape resistance. The resistance surface is used to reflect the trend of landscape elements and realize the spatial coverage [28]. The resistance surface is usually established in studies by using the minimum cumulative resistance model. In the establishment of this model, three factors, namely, source, landscape interface characteristics, and distance between source and landscape interface, are considered. The formula is [29,30]:

$$MCR = f \min \sum_{j=n}^{i=m} (D_{ij} * R_i)$$

where MCR reflects the resistance value between “source” and “landscape interface”; *f* is an unknown functional expression that reflects the minimum resistance of a point in space, and its numerical value is positively related to the distance of the source and the feature of the landscape base surface; *i* is the characteristic of the landscape base surface; *j* is the source of the landscape element; *D_{ij}* is the spatial distance of the species from a certain point

in space to the base surface i of the landscape traversed by source j ; and R_i is the resistance coefficient of landscape base surface i to species crossing the landscape base surface.

The function f is usually unknown, but its value can be measured by the relative accessibility of the cumulative value of (D_{ij} times R_i). The magnitude of the resistance value from all sources to a point is used to measure the accessibility of the point.

Establishing an integrated security pattern through the single security pattern is the third step. Using the inflection and division points in the buffer zone, the integrated security pattern is divided into three parts, “minimum safeguard pattern”, “optimal pattern”, and “less influential pattern”, to demarcate different levels of a single security pattern. Based on the equal-weighted overlay, the “minimum security pattern”, the “optimal pattern”, and the “less influential pattern” are formed. The “minimum security pattern” is composed of the most important source and key areas of the ecosystem. It is the “core area” of the important landscape element safety pattern and is also considered the insuperable ecological bottom line of urban construction. In general, construction zoning should be included within an area of prohibited construction. The “optimal pattern”, as the natural ecosystem and artificial system material and the energy convergence and communication site, is the landscape security pattern’s “control area”. Within necessary development and construction activities, we should first assess the influence exerted from the optimal pattern to the core area, and after that, assess what development and construction activities could happen. In general, it should include the restricted construction zone. The “less influential pattern” has less of an impact on the surrounding ecological environment and is suitable for development and construction.

2.2. Simulate Urban Spatial Expansion

Cellular automata (CA) is a local grid dynamic model in which there is interaction in space and causality in time, but the state in space and time are discrete [31]. Combined with the present situation of developed urban land, we can use CA to simulate future scenarios of urban spatial expansion [32–34]. To determine the total number of cells to be converted, the spatial distribution of urban construction space corresponding to the total amount of development is simulated based on spatial constraints to the total developable amount (i.e., urban spatial pattern). Based on the multi-criteria judgment, the concrete operational flow of building a CA simulating urban construction land expansion is given in Figure 2.

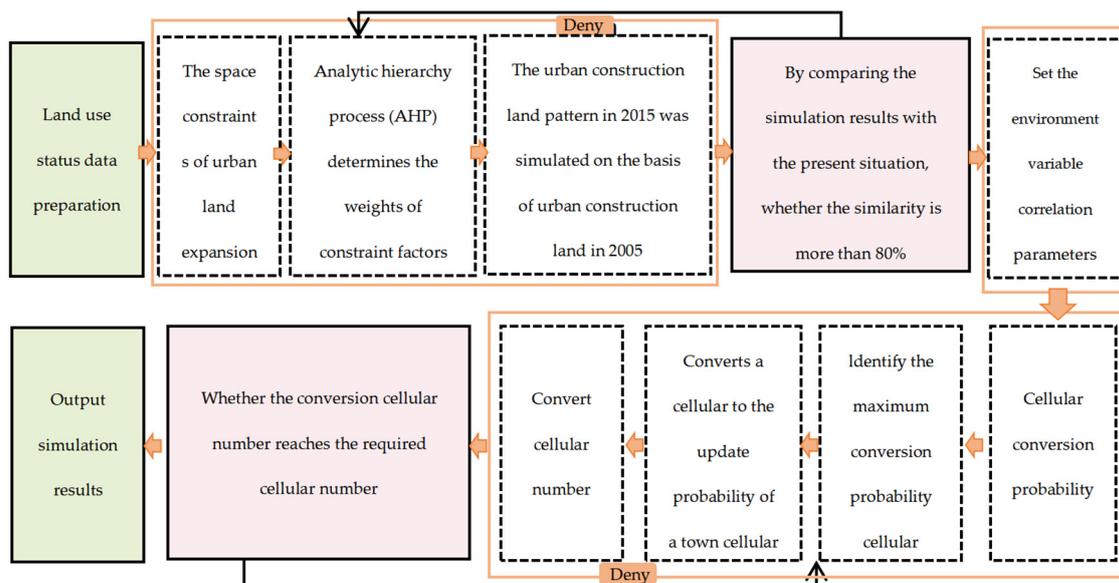


Figure 2. Flow of cellular automata simulation of urban expansion (derived from “Exploring the effects of partitioned transition rules upon urban growth simulation in a megacity region: a comparative study of cellular automata-based models in the Greater Wuhan Area”).

divided into “minimum safeguard pattern” (expressed as A), “optimal pattern” (expressed as B), and “less influential pattern” (expressed as C). By superimposing three conditions of urban construction and three conditions of landscape pattern based on ArcGIS 10.2, nine different patterns are explored (Figure 4).

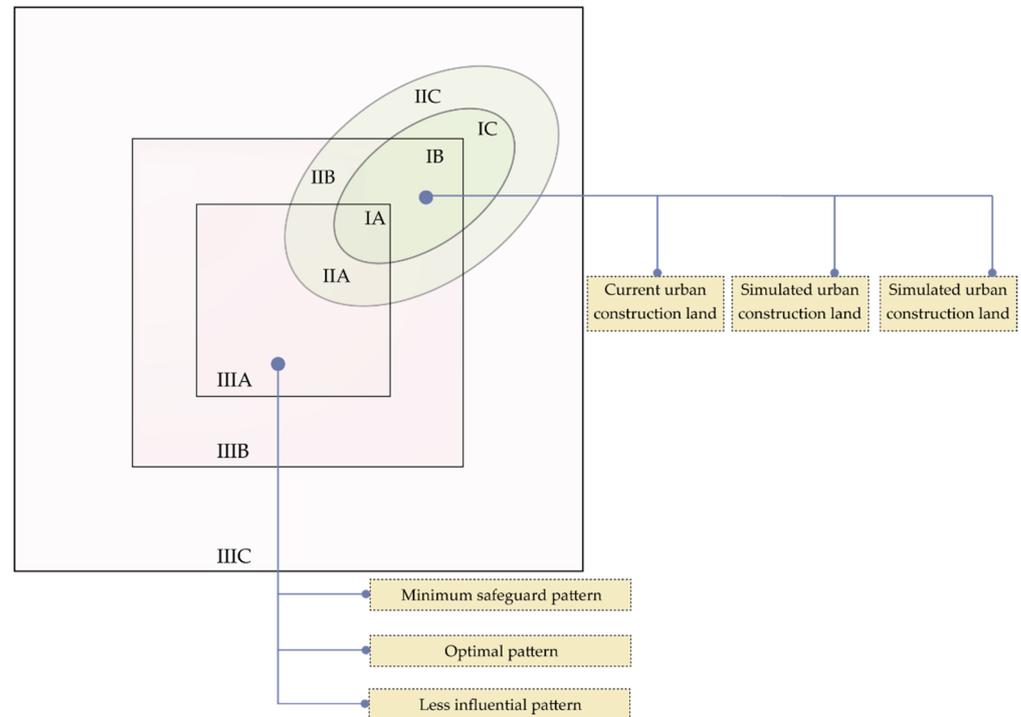


Figure 4. Analysis diagram of urban spatial regionalization method.

Case 1 (IA): The overlapping area between “current urban construction land” and “minimum safeguard pattern” of the integrated security pattern.

In the spatial regionalization, the construction land should be adjusted, and the corresponding compensation should be made in the area where the landscape safety threat is small. The adjusted land boundary should be regarded as the rigid growth boundary and classified as the prohibited construction zone. Although the current situation is construction land, it is likely to be affected by factors such as landslides, floods, etc. In this case, it will not be suitable for construction and thus is classified as a prohibited construction zone.

Case 2 (IB): The overlapping area between “current urban construction land” and “optimal pattern”.

Corresponding adjustments should be made in the spatial regionalization, and corresponding compensation should be made in areas where the landscape safety threat is also small. The adjusted land boundary should be regarded as the elastic growth boundary and divided into the restricted construction zones.

Case 3 (IC): The overlapping area between “current urban construction lands” and “less influential pattern” is small.

In the spatial regionalization, this should be located within the boundary of elastic growth, and it should be assigned to the suitable construction zone.

Case 4 (IIA): The overlapping area between “simulated urban construction land” and “minimum safeguard pattern”.

In the spatial regionalization, the construction land should be adjusted, and the corresponding compensation should be made in the area where the landscape safety threat is small. The adjusted land boundary should be used as a rigid growth boundary and classified into the prohibited construction zone.

Case 5 (IIB): The overlapping area between “simulated urban construction land” and “optimal pattern”.

In the spatial regionalization, the construction land should be adjusted, and the corresponding compensation should be made in the area where the landscape safety threat is small. The adjusted land boundary should be regarded as the elastic growth boundary and classified into the restricted construction zone.

Case 6 (IIC): The overlapping area between “simulated urban construction lands” and “less influential pattern” does not affect landscape security.

In the spatial regionalization, the scope of land use is regarded as the boundary of elastic growth, and it is assigned to the suitable construction zone.

Case 7 (IIIA): The overlapping area between “out-of-reach urban construction land” and “minimum safeguard pattern”.

This case is classified into the prohibited construction zone in the spatial regionalization.

Case 8 (IIIB): The overlapping area between “out-of-reach urban construction land” and “optimal pattern”.

This case is assigned to the restricted construction zone in the spatial regionalization.

Case 9 (IIIC): The overlapping area between “out-of-reach urban construction lands” and “less influential pattern”.

The urban construction cannot yet extend to the overlapping land area with less landscape impact. Because this state is temporary, to prevent urban expansion, it should be classified into the restricted construction zone in the spatial regionalization.

In summary, the prohibited construction zoning includes three cases, IA, IIA, and IIIA; the restricted construction zone includes four cases, IB, IIB, IIIB, and IIIC; and the suitable construction zoning includes two cases, IC and IIC.

3. Research Area and Data

3.1. Research Area

Xi’an is located in Guanzhong Plain in the central Yellow River basin ($107^{\circ}40'–109^{\circ}49'$ E and $33^{\circ}39'–34^{\circ}45'$ N). Xi’an is bounded by the Qinling Mountains to the south and Weishui River to the north, and has a long history and a large number of historical and nature reserves. Urban construction land is divided by rivers, and the surrounding mountains provide natural barriers to urban expansion (Figure 5).

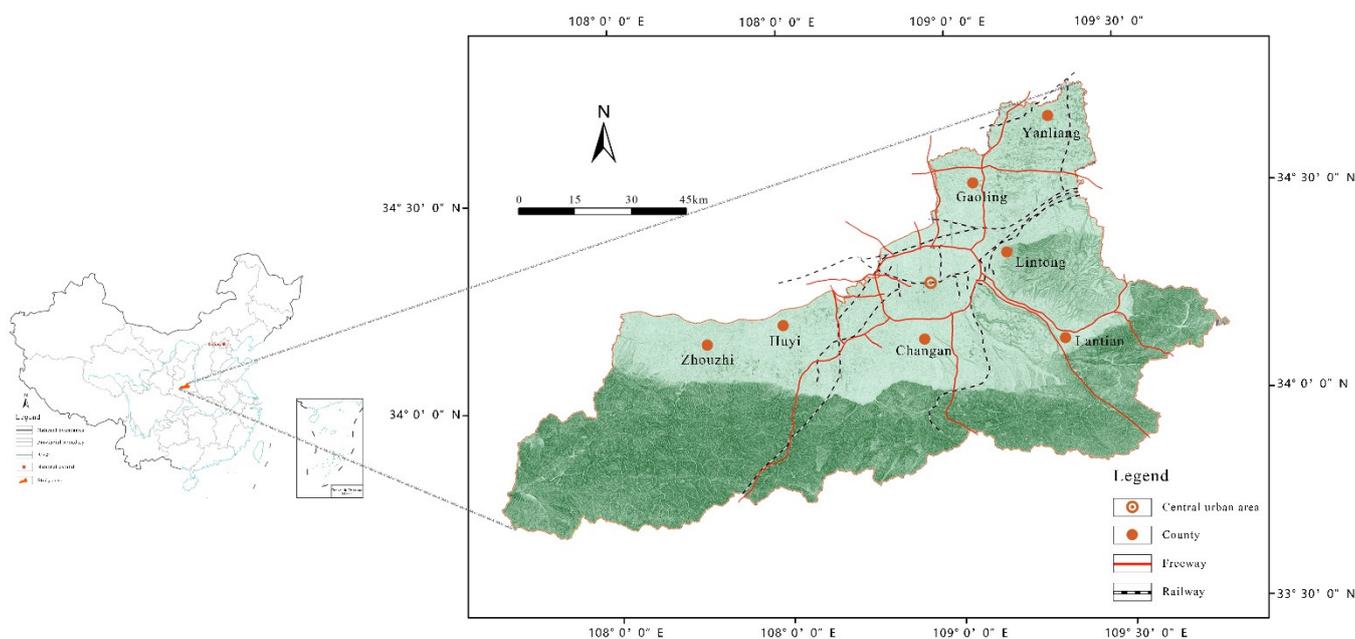


Figure 5. The research area.

With the accelerated urbanization process, increasing socio-economic status, and available space, Xi’an continues to spread. The city has experienced the most rapid urbanization

in its history in the past 25 years, and construction has expanded the city's area from 148 km² in 1993 to 683 km² in 2017 (4.61×). As a pilot city of ecological restoration and urban renovation (a policy of urban governance in China) and delineation of urban development boundaries, Xi'an has interesting research features as it links landscape security patterns to urban spatial control to prevent urban sprawl, promoting the efficient use of land and ensuring the safety of urban landscape elements, among others.

3.2. Data

Urban population data were obtained from the 1993 to 2017 *China City Statistical Yearbook* and *Shaanxi Statistical Yearbook*. We obtained 30 m resolution DEM data and 500 m resolution MODIS data from the Geospatial Data Cloud website, and rainfall data from the China Meteorological Administration. Basic farmland, historical heritage, scenic viewpoints and parks, water resources, natural disaster sites, and other data were from the special planning database of Xi'an. The urban area data were obtained by interpreting land use maps in shapefile format in 2005 and 2015 in Xi'an City. We used the Conversion Tool Raster to ASCII function module in ArcGIS (version 10.2) [36]; the urban status and spatial constraints data were converted to ASCII code file and loaded into GeoSOS, then the urban spatial expansion was simulated by using the Conversion Tool module to use the Raster To ASCII function (ArcGIS10.2). For convenience of interpretation, the area data of Xi'an were converted into a 30 × 30 m raster.

4. Results

4.1. Integrated Landscape Security Pattern

The comprehensive water safety, geological disaster safety, cultural heritage safety, and recreation and entertainment safety patterns (Figure 6) were superimposed with equal weights to construct the integrated landscape safety pattern in Xi'an (Figure 7).

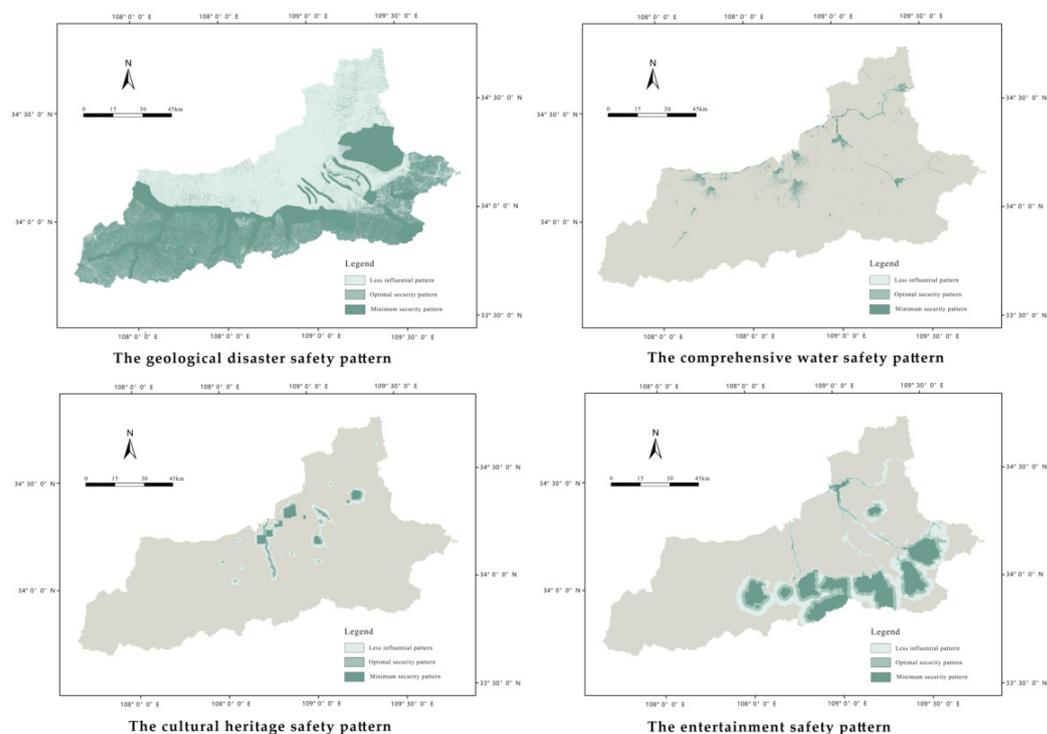


Figure 6. Single landscape security pattern.

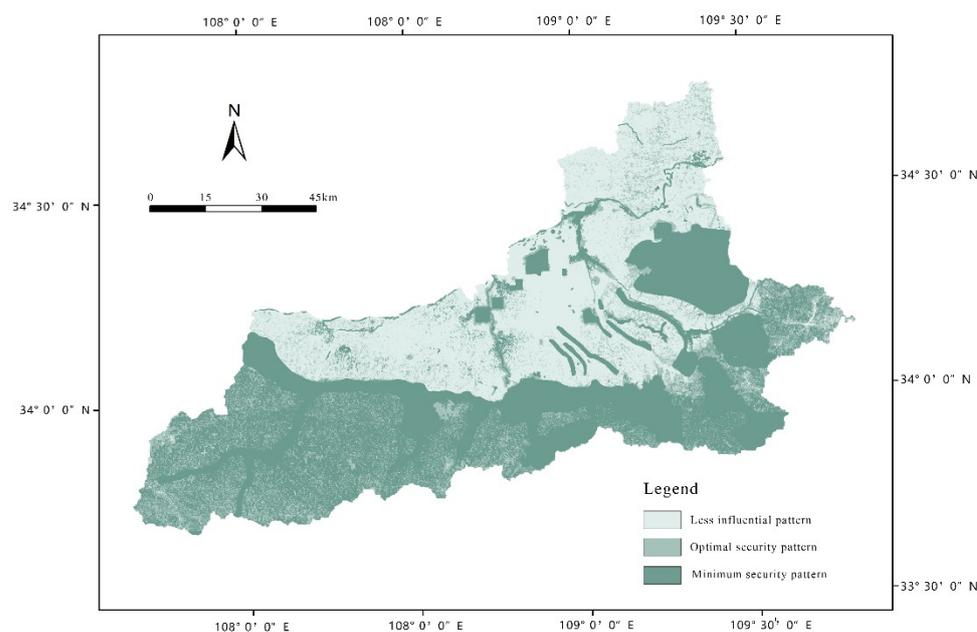


Figure 7. Integrated landscape security pattern.

The integrated landscape security pattern is roughly divided into north and south Xi'an. Due to the influence of the Qinling Mountains, the comprehensive safety pattern primarily appears as a planar distribution in the southern part of Xi'an, which has the matrix characteristics of the ecological landscape. The land in the northern area of Xi'an is primarily urban and rural construction and cultivated. This region is interspersed with rivers, cultural heritage sites, urban parks, and other landscape elements. Altogether, the comprehensive security pattern in the northern area of Xi'an appears point-like in a linear distribution with the plate and corridor features of ecological landscape science.

Within the study area, the land is dominated by the "minimum safeguard pattern" and the areas with small landscape impact. The areas of the "minimum safeguard pattern", the "optimal pattern", and the "less influential pattern" account for 61.1%, 20.7%, and 18.2% of the land use area of Xi'an, respectively. According to the land use distribution, the "minimum safeguard pattern" is primarily distributed in the Qinling Mountains, the main river, and the important cultural heritage sites, but less in other land use sites in Xi'an. The "optimal pattern" is mainly distributed near the "minimum safeguard pattern", which is the buffer zone of the "minimum safeguard pattern", occupying less area. The areas of the "less influential pattern" are primarily distributed in the areas of urban and rural construction as well as cultivated land.

4.2. Simulation of Urban Spatial Expansion

Based on the land use status data in 2015, we simulated the urban spatial expansion in Xi'an in 2030 with the support of GeoSOS software. In the simulation of spatial expansion, the number of urban cells will increase by 116,766 in 2030. The simulation results of urban spatial expansion are shown in Figure 8. The landscape security is threatened as urban construction land spreads outward. The increase in the urban population will further promote the increase in urban construction land demand, and then the construction land in the main urban area will be further integrated with the surrounding construction land, occupying the cultivated land, landscape land, and other land. Urban construction land will inevitably encroach on the surrounding landscape land, and pose a serious threat to landscape security. Based on the 2015 land use status data, we simulated urban spatial expansion in Xi'an in 2030 using GeoSOS software. In the simulation of spatial expansion, the number of urban cells increased by 116,766 in 2030 (Figure 8). Landscape security is threatened by the outward spread of urban construction. The increase in urban

population further increased demand for urban construction, expanding the main urban area, further integrating it with the surrounding construction, and occupying the cultivated land and lands of non-urban use. Urban construction land will inevitably encroach on the surrounding landscape and pose a serious threat to landscape security.

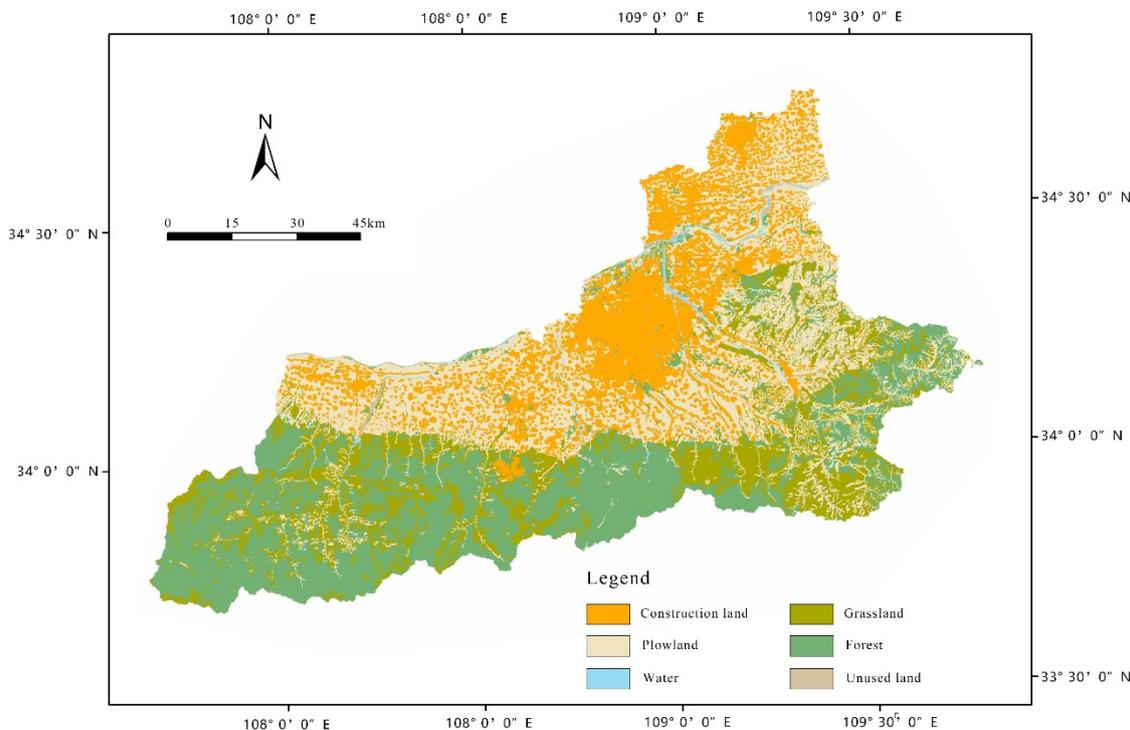


Figure 8. Simulation diagram of land scope for urban construction in 2030.

The growth rate of the central city is faster than that of the marginal region. Due to the relatively complete infrastructure (transportation, services, etc.) in the central urban area, it is more attractive to residents than the peripheral cities. Therefore, the growth rate of urban construction land in the downtown area is much faster than that of the surrounding urban areas. Although construction in other counties and towns has also increased, the newly increased urban construction is primarily in the vicinity of central urban areas.

The expansion intensity of the southern region is greater than that of the northern region. In recent years, the urban area of Xi'an has primarily expanded to the southwest, as the space of the southern region is wider than that in the north. The space in the south is restricted by ecological protection, such as that created by the northern slope of the Qinling Mountains, limiting space for further development to the south. In relative terms, although the northern part of the urban space is smaller, both the land conditions and the development environment are better. Therefore, the emphasis of the development and construction of Xi'an should be shifted to the north of the central city as the urban area expands.

4.3. Identification Urban Spatial Zoning

To strengthen spatial regulation, spatial zoning divides the area into suitable, restricted, and prohibited construction zones. Permanent primary farmland (in China, according to an era with a given population and social economy demand for agricultural products, on the basis of general land use planning, development may occur on cultivated land) shall not take up the urban construction land, and cannot be converted to be included in the ban on these areas. This is comprehensively defined for other areas and put forward in corresponding management plans (Figures 9 and 10).

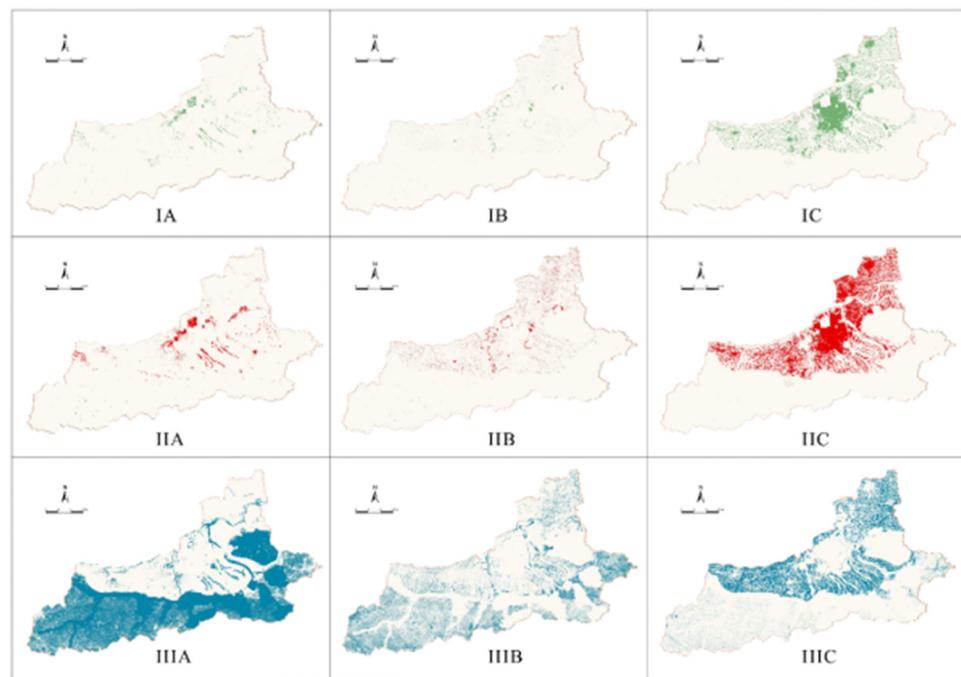


Figure 9. Modes of spatial control zoning. (IA-IIC derived from Figure 4).

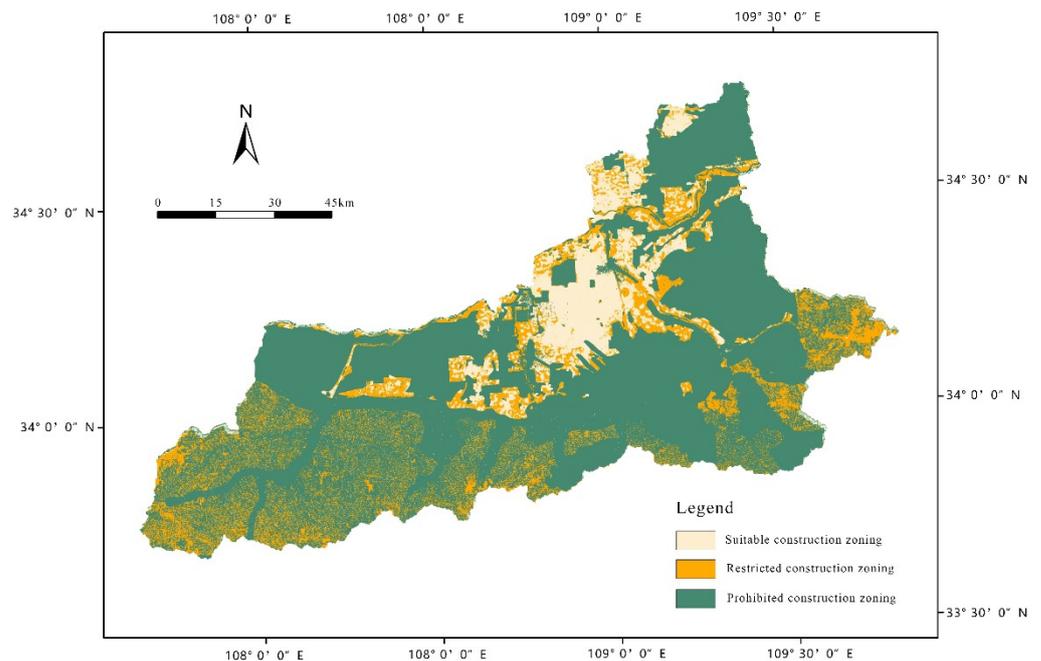


Figure 10. The integration result of urban spatial control zoning.

Suitable construction zones (IC and IIC) are located near the main urban area of the current urban construction land, accounting for 10.4% of the total area. From the perspective of spatial distribution, urban construction and the surrounding land are further integrated into a whole. However, in terms of the spatial size, the area of urban construction land becomes gradually smaller from the main urban area to the surrounding areas. For the urban land within this zone, different functional zones should be planned to effectively improve urban functional structure and promote sustainable land use development. This should be the primary area to promote urbanization, and the policy should be flexible with reasonable development intensity indicators formulated according to external conditions.

Combined with urban renewal and extension, this promotes the redevelopment of low-use land and improves overall land use efficiency.

The restricted construction zones (IB, IIB, IIIB, and IIIC) are primarily distributed in the area surrounding the main urban area—i.e., between the prohibited construction and the suitable construction zones, accounting for 14.7% of the total area. The current situation in the restricted construction zone primarily includes rural construction, cultivated, and other lands, and land use is more sensitive. It is necessary to strictly restrict the development of urban construction land, resolutely dismantle facilities that affect ecological landscape safety, properly include tourism opportunities with recreational value such as scenic spots. Therefore, this area should adhere to ecological priority, strengthen environmental protection and regional ecological restoration, be attentive to current construction, control new construction land, and develop ecologically relevant advantageous industries that sustainably bear the resources and environment under local conditions.

The prohibited construction zones (IA, IIA, and IIIA) are primarily distributed in the Qinling Mountains, and areas of cultural heritage protection, high-risk geological disasters, water system reserves, recreational and entertainment, and permanent basic farmland area, accounting for 74.9% of the total area. To maintain an effective ecological environment and realize the goals of sustainable urban development, urban construction activities in the prohibited construction zones should be strictly controlled; any other construction activities within the zones should be strictly prohibited along with the necessary protection facilities.

5. Discussion

Optimizing the spatial growth pattern and improving the efficiency of land and resources use are still long-term goals for land and resources management and regional development in China. With increasing urbanization and the expansion of developed area, land use planners face three primary challenges: determining how to use landscape planning and design to scientifically achieve ecosystem goals, promoting sustainable urban development, and mitigating the negative effects of urbanization [37,38]. We suggest that excessive urban expansion leads to the fragmentation of both urban living spaces and ecosystems; nevertheless, it is unclear how to effectively expand urban space and remain sensitive to landscape security. Urban spatial zoning is defined by landscape security and urban spatial expansion perspectives. In this process, landscape security and urban spatial expansion are two key elements that should not be neglected. Considering these perspectives can ensure the security of the urban landscape pattern and promote smart urban growth [39].

Spatial control areas and measures based on anti-planning theory are effective in the protection of urban landscape security [40]. However, urban development and landscape security changes are affected by several natural and socioeconomic factors. More research is necessary to understand these pressures, and they should be incorporated into future CA models in support of quantitative predictions for future urban development [41] consistent with reasonable arrangements of urban spatial structure [42]. We explored the dual urban spatial zoning perspectives of landscape security and spatial planning, which realized landscape security and satisfied urban spatial expansion [43]. Our approach effectively made up for the deficiencies of single-perspective predictions. This is particularly important in China, a developing country that focuses on urban spatial expansion, to maximize ecological and environmental benefits through scientific and efficient land management while making efficient use of ecological resources while considering protection.

Different modes of land use development can better realize smart land management [44]. However, different land types permit diverse forms of expansion across development periods, making it difficult to predict targeted measures that will achieve smart land management. More detailed and finely demarcated zoning, especially in areas with a high probability of urban growth, produces more accurate forecasts. Based on the landscape security pattern and simulations of urban spatial expansion, nine different modes of land spatial regulation were identified here, which were effective for spatial zoning and opti-

mization of land resource allocation. This kind of spatial overlay scenario analysis based on ArcGIS maps patch segmentation enables land managers to judge the influencing factors and formulate corresponding spatial control countermeasures. Spatial regulation scenarios can promote the benign interaction between landscape protection and urban development and realize the real-time dynamic control of land.

Cities are giant, complex systems [45]; society, economy, environment, urban development, and many other factors influence urban spatial expansion [46]. Therefore, along with urban development, it is necessary to study the future development of cities. It was our intent to explore a new and refined landscape safety management and zoning model. A differentiated partition control model with strong continuity and high cohesion is conducive to the seamless coverage of a complete control policy and the visualization of enduring stability and sustainable development of regional ecology and landscape security.

Although we achieved some success, there remain three challenges that should be further investigated. (1) In the actual management process, comprehensive consideration of influencing factors is needed to make the next step in control measures more rational and feasible. (2) In the CA spatial expansion simulation, determining land conversion thresholds is somewhat subjective, which can affect the simulation results. Future research should consider objectively determining urban land conversion thresholds. (3) CA and least-resistance models are not the only ways to build this architecture. Alternative approaches that reflect and build this architecture should be tested. With this in mind, we encourage the establishment of a spatial control zoning model system. It should be based on landscape security and urban expansion to explore the effects of urban zones and identify suitable routes for urban development. This approach permits the simultaneous study of the future development trajectory of different cities, analyzes their identities and differences, and improves the applicability of the research.

6. Conclusions

Using multiple perspectives of landscape security and intelligent urban growth, we proposed a theoretical framework of landscape security patterns for urban space expansion. Taking the city of Xi'an as an example, we systematically modeled scenarios of urban expansion and spatial control zoning, recommending detailed management measures for each zone.

The nine spatial expansion scenarios reflect the most possible future land uses in different areas of the city. Spatial control zones also create conditions for the refined control of city development. Importantly, the theoretical framework of landscape security patterns for urban spatial expansion occurs from the perspective of ensuring a win-win of urban development and landscape protection. CA and the least resistance model are not the only methods to model this system, and alternatives should be considered.

Compared to the single perspective of either landscape security or urban expansion, considering multiple urban space controls in the city's economic development simultaneously encourages robust urban landscape ecological security. Such models should be sufficient to reduce the impact of development and construction of natural environments, provide suitable conditions for sustainable long-term development for the city's protection, and prevent the spread of disorder to achieve smart urban growth.

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