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A Multi-Scenario Prediction and Spatiotemporal Analysis of the Land Use and Carbon Storage Response in Shaanxi

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Abstract: The role of carbon sequestration in terrestrial ecosystems is crucial for achieving carbon neutrality. This study primarily focuses on examining the carbon storage in Shaanxi Province under different land-use scenarios. This study employed the LP-PLUS-InVEST model to explore the characteristics and spatial and temporal changes in carbon storage across four scenarios (business-as-usual (BUS), ecological protection (EPS), water–energy–food (WEF), and rural revitalization (RRS)) in Shaanxi Province. The results show that from 2000 to 2020, the carbon storage in Shaanxi Province is on a decreasing trend mainly due to the large occupation of ecological land by economic development. EPS has the largest increase in carbon storage under the four scenarios in 2030 and 2060. On the contrary, BUS has a rapid expansion of construction land, which leads to a gradual decreasing trend in carbon storage. WEF has a gradual increasing trend in carbon storage, while RRS has a trend of increasing and then slowly decreasing carbon storage. The spatial distribution trends of carbon storage in all scenarios were similar; high-carbon-reserve areas were mainly distributed in southern and central Shaanxi, which has a better ecological environment and less construction land, while low-value areas were distributed in the Central Shaanxi Plain, which has high land-use intensity. In terms of the stability of carbon reserves, the stable areas are predominantly concentrated in the Qinling Mountains, while the unstable areas are concentrated in the plain urban areas. Specifically, returning cultivated land to forest and grassland is an important initiative to promote the increase in carbon storage in Shaanxi Province. The decrease in carbon storage is mainly affected by strong urban expansion. Our study optimizes the land-use pattern according to the development needs of Shaanxi Province, and promotes the integrated development of ecological protection, food security, and economic development. Guidance is provided to promote regional carbon neutrality.

Keywords: land-use change; carbon storage; multi-scenario simulation; rural revitalization; water–energy–food nexus; Shaanxi Province

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1. Introduction

China has established carbon peaking and carbon neutrality as future development goals in response to the climate crisis, reflecting the country's positive attitude toward building a shared future community for humanity [1]. Becoming carbon neutral means achieving net zero greenhouse gas emissions [2]. Terrestrial ecosystems can fix CO_2 and play a vital role in carbon sequestration [3]. Moreover, carbon sequestration in terrestrial ecosystems is currently the most cost-effective, safe, and straightforward way to reduce CO_2. Thus, enhancing the carbon sequestration capacity in terrestrial ecosystems is crucial to achieve carbon neutrality [4]. Land-use change has the potential to alter the internal function and condition of terrestrial ecosystems, leading to dynamic changes in regional carbon storage [5]. Different land-use types have different carbon sequestration capacities [6,7]. Therefore, it is essential to explore ways to optimize land-use structures to enhance regional carbon storage to ultimately cope with the climate crisis and achieve a regional carbon balance.

In recent years, researchers have investigated the carbon storage of terrestrial ecosystems through various methods, including field investigations [8], remote sensing estimations [9], and model simulations [10]. They have explored the temporal and spatial dynamics of carbon storage from different perspectives and scales and studied the mechanisms underlying the carbon balance. Widely used carbon storage estimation models, such as the CASA model [11], FORCCHN model [12], LPJ-GUESS model [13], and DNDC model [14], present challenges for data accessibility and usability. In contrast, the InVEST model has the advantage of calculating carbon storage with fewer data requirements, making it a widely used model for carbon storage calculation [15]. Therefore, this study applied the InVEST model to calculate carbon storage. The CA-Markov model [16] and the CLUE-S model [17] can serve as useful tools for future land-use scenario studies. However, the PLUS model [18] has the capability to include constraints and potential development factors, resulting in more accurate simulations of future scenarios and enhanced modeling of land-use development under different scenarios.

Existing studies have examined and quantified the effects of land use on carbon storage at different scales and in different landscapes [19–21]. The results show that land use changes soil properties and vegetation cover [22], leading to changes in regional carbon storage. Further, more efficient and scientific land use and optimization of a land pattern to achieve carbon sequestration and emission reduction is now a high concern of researchers [23–26]. Spatial pattern optimization is currently an important means to solve the contradiction between economic development and ecological protection. Optimization of land use has shifted from the short-term goal of focusing on economic development to the long-term goal of protecting a good ecological environment [27,28]. At present, many researchers have studied the carbon storage response under the optimization of a land-use pattern for different purposes, including the optimization of a land-use pattern with the goal of protecting cultivated land [29,30], the goal of economic development [31], or the goal of ecological protection [32]. From the results of a large number of studies, it can be seen that land use with the goal of ecological protection will enhance the regional carbon storage, and most of the land use with the goal of economic development will damage the ecological environment to a certain extent and lead to a large reduction in carbon storage [33]. However, these objectives lack consideration of the integrated optimization of economic development, ecological protection, and rural development, and do not consider the overall changes in different functional areas of the region. Therefore, it is necessary to further study how to reduce regional ecosystem vulnerability. Optimization of land use enables regional carbon storage and ecosystem loss and degradation to be addressed.

This study aims to provide valuable insights into land-use changes and carbon storage dynamics in Shaanxi Province. We analyze the relationship between land-use scenarios and carbon stocks from 2000 to 2020. And the LP model is used to optimize future land-use patterns, followed by the PLUS and InVEST models to simulate carbon storage under various scenarios in 2030 and 2060. Notably, we present innovative considerations for incorporating the water–energy–food scenario and rural revitalization scenario into our analysis. By extracting stable and unstable regions of carbon storage changes, this research enhances land-use planning and resource allocation strategies. Moreover, our study contributes to the regional carbon balance in Shaanxi and provides a scientific foundation for achieving carbon neutrality.

2. Materials and Methods

2.1. Study Area

This study takes Shaanxi Province as the study area. Shaanxi Province is positioned in the central part of China (as depicted in Figure 1) and spans an area of approximately 205,600 km^2. It is recognized as the most economically developed province in the northwestern region of China. Spatial patterns of carbon intensity are strongly correlated with climatic variables [21]. Shaanxi Province, in the heart of China, serves as a unique case study to explore the diverse climate characteristics between its northern and southern regions, which are separated by the Qinling Mountains. The northern zone's climate is typified with a temperate continental climate with desert-like features, while the Guanzhong Plain area possesses a temperate monsoon climate. In contrast, the southern area exhibits subtropical features. Shaanxi has played a vital role in maintaining ecological balance among various ecosystem types, including mountains, rivers, forests, cultivated lands, lakes, and grasslands. However, socioeconomic development and rampant urbanization have triggered ecological degradation, which threatens several key environmental indicators, such as land-use carbon sequestration. To address such negative environmental impacts, Shaanxi has taken a proactive approach and returned cultivated areas to forestland and grassland [34]. Furthermore, a new ecological protection model has been established, facilitating the systematic governance of ecological resources.

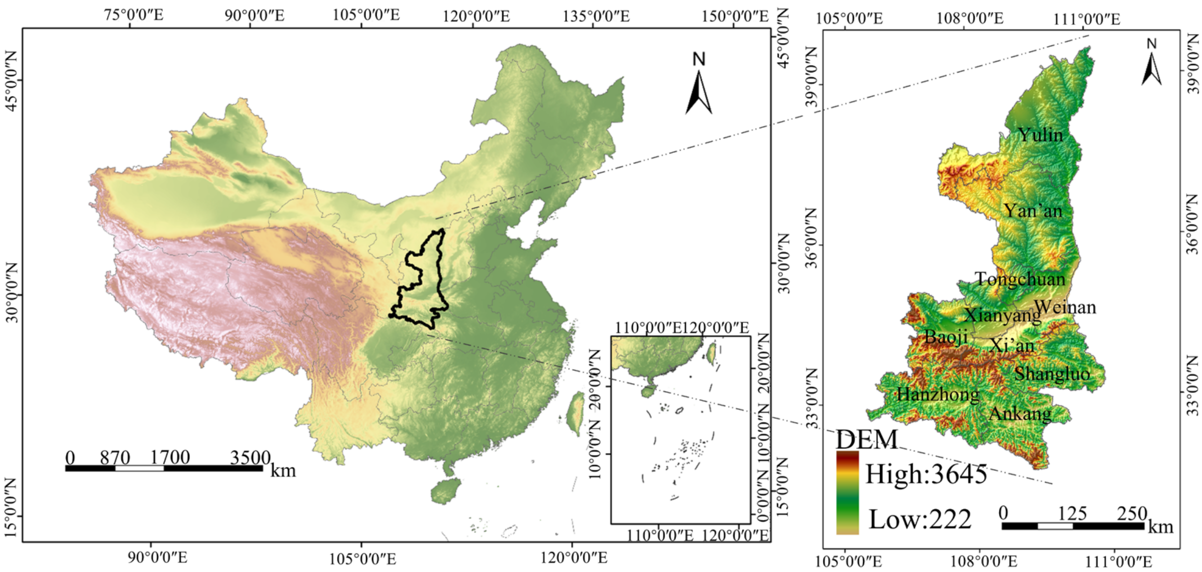


Figure 1. Geographical location and DEM of Shaanxi.

2.2. Data Source and Preprocessing

The LULC data were downloaded from http://www.resdc.cn, accessed on 7 October 2022. In this study, the land-use data used were obtained from remote sensing images, which included Landsat-MSS, Landsat-TM/ETM, and Landsat 8 data. These images were processed through fusion, geometric correction, image enhancement, and mosaic techniques. The data set was obtained by combining these processed images with human–computer interactive visual interpretation methods [35]. For this study, 14 driving factors were selected. DEM data were derived from the Geospatial Data Cloud (https://www.gscloud.cn, accessed on 8 October 2022). Population density, GDP, temperature, and precipitation data come from the Resource and Environmental Science and Data Center. From DEM data processing, elevation, slope, and slope direction were obtained as topographic factors. Road network and river data were derived from Open Street Map. Data from train stations, railway stations, primary urban roads, highways, county roads, and rivers were obtained with Euclidean distance processing. Projection transformation, cropping, and resampling techniques were used to convert these drivers into a format that was acceptable for the modeling process. Throughout the data processing, we ensured that the coordinate systems were uniform and that the number of rows and columns corresponded for each data set.

2.3. Methods

ArcGIS was employed to investigate the land-use pattern and transformation in Shaanxi Province between 2000 and 2020. Furthermore, the InVEST model was used to analyze the distribution of carbon storage in the region during the same period and examine its relationship with land-use changes. In order to achieve this, various development scenarios were formulated based on the existing conditions and development requirements of the study area. The Markov chain was utilized to estimate the extent of land-use development under the BUS [36,37]. A linear programming model was employed to optimize the allocation of land-use requirements in the WEF and RRS land-use patterns, incorporating various constraints. The model aimed to maximize the effectiveness of land use under different circumstances. Additionally, the PLUS model was utilized to incorporate spatial development and restriction policies into the land-use development process, enhancing the overall planning outcome. Further development and restriction factors were set under different scenarios to satisfy the requirements of land use and development under different circumstances. Combined PLUS and InVEST models were used to project regional carbon storage under different scenarios in 2030 and 2060, and a spatial correlation analysis of regional carbon storage was conducted. Stable and unstable areas of carbon storage changes were also quantified and analyzed. The technical roadmap is depicted in Figure 2.

2.3.1. PLUS Model

The PLUS model is a land-use/land cover change simulation model that utilizes raster data [38]. In this study, the remote sensing monitoring data of land use in China were taken as the main data, and the driving factor data were taken as the input data of the PLUS model. This model provides higher simulation accuracy than other traditional models. Additionally, it is more consistent with the actual landscape index [39]. The PLUS model incorporates the LEAS component to analyze the driving factors of land-use expansion and development probabilities for various land-use types. The results from the LEAS part are then utilized in the CARS component for land-use simulation and prediction. This comprehensive method can more accurately simulate the land-use landscape and its dynamic change process.

2.3.2. InVEST Model

In the InVEST model, the carbon storage module calculates carbon storage by utilizing carbon pool data and land-use data [40]. In this study, the carbon density data of different types of land come from the National Ecological Science Data Center (http://www.cnern.org.cn, accessed on 14 October 2022) and refer to related literature. The relevant studies by Xie et al. [41] and Yang et al. [42] as references for aboveground and belowground biomass carbon densities, and studies by Li et al. [43] and Zhang et al. [44] et al. as references for soil carbon densities, then converted using local temperature and precipitation material. Carbon density was modified using existing weather factor adjustment equations [45–47]. Shaanxi carbon density data are shown in Table 1.

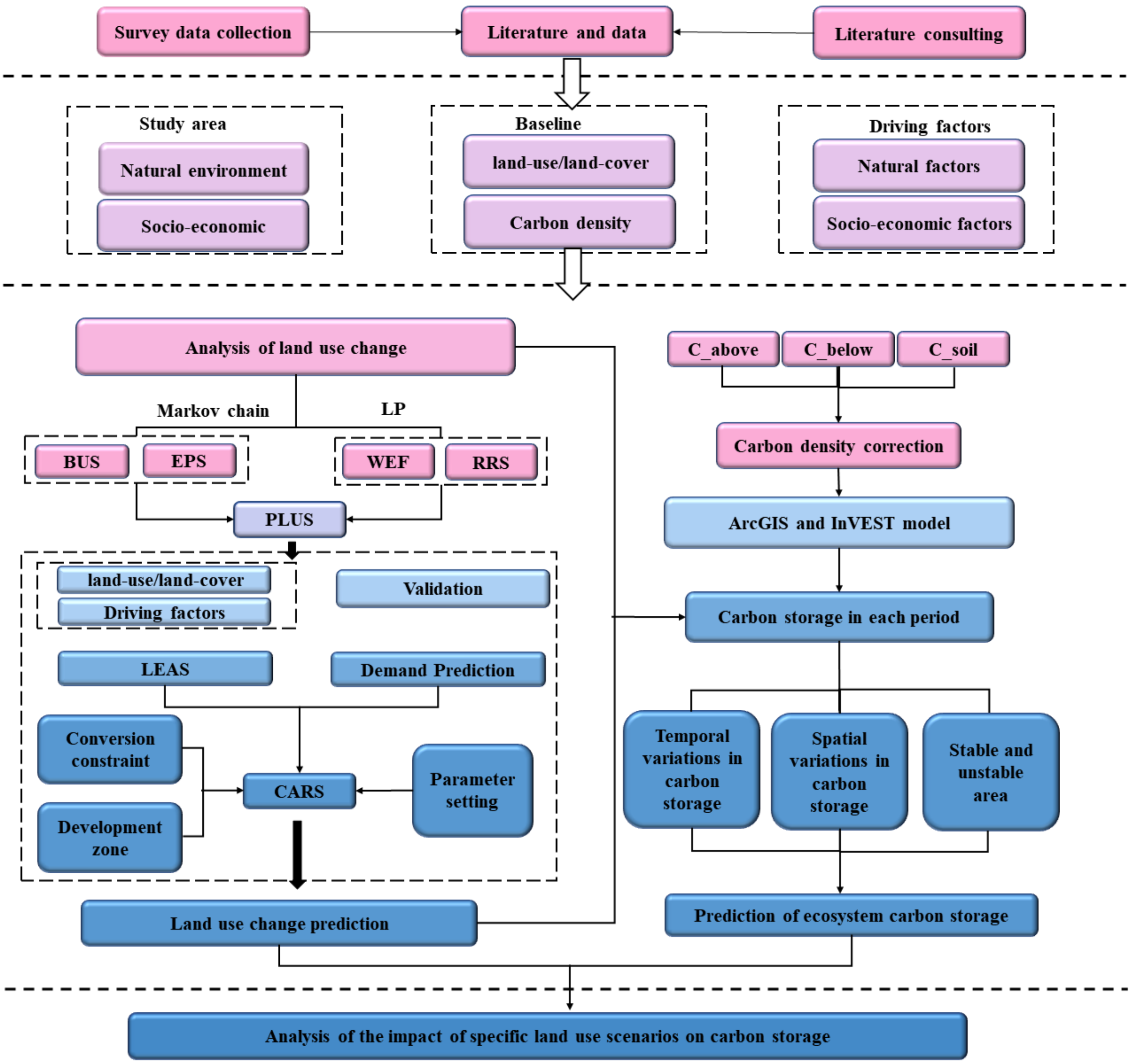


Figure 2. Research framework.

Table 1. Carbon pools.

LULC Class	$C_{\_above}$	$C_{\_below}$	$C_{\_soil}$	$C_{\_dead}$
Cultivated Land	8.1	114.4	110.6	0
Forestland	60.1	164.2	162	0
Grassland	50	122.6	102	0
Water Land	4.3	0	0	0
Construction Land	3.5	0	0	0
Unutilized Land	1.8	0	22	0

2.3.3. Land-Use Scenario Set Up

The business-as-usual scenario (BUS) solely considers current land use and management measures, without factoring in future changes or interventions. This analysis investigates land-use changes based on land-use management measures implemented from 2000 to 2020. Using 2020 as the base year for future predictions, the PLUS model is employed to simulate changes in carbon reserves following the base year. In other words, this scenario extends and builds upon the ongoing trends of carbon storage changes, with no significant changes observed in the relevant policies.

The ecological protection scenario (EPS) prioritizes ecological conservation over economic development. This scenario imposes limitations on the expansion of productive land for immediate gains while simultaneously reducing the conversion of forests, grasslands, and cultivated land for this purpose. This scenario aims to improve the regional ecological environment by increasing the area of forestland, grassland, and water. Moreover, it designates national nature reserves as restricted areas, thus encouraging the development of ecological civilization.

The water–energy–food scenario (WEF) ensures proper water retention for production and living while prioritizing ecological protection. This scenario limits water transfer to other areas and optimizes regional carbon sequestration capacity. It views water as the foundation of development and ecological protection, with food security and energy infrastructure as restraints. By establishing a suitable land-use structure, the WEF aims to secure the quality of cultivated land growth.

The rural revitalization scenario (RRS) aims to achieve harmony between people and nature, promote economic development in rural areas, and realize urban—rural integration. It strives to create a harmonious balance between nature and humanity, urban—rural integration, and rural district invigoration. The RRS primarily uses county roads to drive land-use change while also appropriately expanding space for forestland, grasslands, and production to enhance ecological livability in rural areas. Linear programming optimizes land-use quantity, and the linear programming models improve demand quantity.

This analysis utilizes Multi-Linear Programming to set WEF and RRS as future land-use pattern predictors. The carbon storage calculation equation was converted into a multivariate linear programming equation to determine the maximum carbon storage capacity. The study area's basic conditions and expected development requirements serve as constraints. The linear programming model is presented below:

$$F(x) = \sum_{i=1}^{6} C_i \times A_i \tag{1}$$

In the formula, $F(x)$ is the total carbon storage; C_i is the carbon density; and A_i is the area of each land-use pattern, which is the decision variable. (A is water–energy–food scenario and A' is rural revitalization scenario.)

The formula of the linear programming model is as follows:

$$MAX = 233.1 \cdot A_1 + 386.3 \cdot A_2 + 274.6 \cdot A_3 + 4.3 \cdot A_4 + 3.5 \cdot A_5 + 23.8 \cdot A_6 \tag{2}$$

The setting of constraints mainly refers to relevant planning and policies and comprehensively considers the social and economic growth essentials of Shaanxi.

1. Water–energy–food scenario

To ensure high-quality agricultural development and promote ecological conservation, this scenario has as its primary constraint the promotion of water conservation and the suppression of arable land reduction. The annual growth rate of water should be above 0.5%, and the annual rate of decrease in grassland and water should not exceed 0.2%. To safeguard food security, the WEF must adhere to a cultivated land protection red line while strictly regulating nonagricultural construction on agricultural land. The plan aims to maintain national cultivated land reserves of 1.243×10^6 km^2 and 1.216×10^6 km^2 for 2020 and 2030, respectively. Therefore, this scenario's annual reduction rate of cultivated land is at least 0.5%. This scenario will increase the annual growth rate of forestland by 0.5% and grassland by at least 0.1% to promote ecological development. Given Shaanxi's current socioeconomic development and its land-use intensity limitations, productive land growth should be limited to 1.02%.

Based on the above conditions, the constraints of decision variables are as follows:

$$\sum_{i=1}^{6} A_i = 205705.38\ ;\ A_i \geq 0 \quad (3)$$

$$A_1 > (1 - 0.5\%)^n \times 66371.77 \quad (4)$$

$$(1 + 0.5\%)^n \times 48819.67 < A_2 \leq (1 + 2\%)^n \times 48819.67 \quad (5)$$

$$A_3 \geq (1 - 0.2\%)^n \times 79530.01;\ A_4 \geq (1 + 0.2\%)^n \times 1816.23 \quad (6)$$

$$(1 + 0.1\%)^n \times 4678.07 < A_5 \leq (1 + 1.02\%)^n \times 4678.07 \quad (7)$$

$$(1 - 0.97\%)^n \times 4489.62 < A_6 \leq (1 + 0.5\%)^n \times 4489.62 \quad (8)$$

2. Rural revitalization scenario

To promote rural revitalization and urban—rural integration, county roads should be used as the main influencing factor of LULC change. Furthermore, cultivated land's annual diminish rate should be below 1%. In comparison, the annual growth rates of forestland and grassland should not be lower than 0.5% and 0.1%, respectively, with a minimum growth rate of 0.1% for watersheds. Regarding productive land, efficient use of existing construction-using land in rural areas and a moderate increase should be implemented, with a growth rate of 0.5–1.02%.

Based on the above conditions, the constraints of decision variables are as follows:

$$\sum_{i=1}^{6} A'_i = 205705.38\ ;\ A'_i \geq 0 \quad (9)$$

$$A'_1 \geq (1 - 1\%)^{\ n} \times 66371.77 \quad (10)$$

$$(1 + 0.5\%)^n \times 48819.67 < A'_2 \leq (1 + 2\%)^n \times 48819.67 \quad (11)$$

$$A'_3 \geq (1 + 0.1\%)^n \times 79530.01; A'_4 \geq (1 + 0.1\%)^{\ n} \times 1816.23 \quad (12)$$

$$(1 + 0.5\%)^n \times 4678.07 < A'_5 \leq (1 + 1.02\%)^n \times 4678.07 \quad (13)$$

$$(1 - 0.97\%)^n \times 4489.62 < A'_6 \leq (1 + 0.5\%)^n \times 4489.62 \quad (14)$$

2.3.4. Spatial Correlation Analysis Based on Grids

This study conducts a spatial autocorrelation analysis on a grid scale to achieve greater evaluation granularity. The pre-generation of nets and grid points, followed by overlaying them with existing data, is necessary for a grid-scale spatial correlation analysis. Moran's I, as a global spatial autocorrelation calculation method, is employed to detect the presence of a spatial agglomeration model in the distribution of carbon reserves in Shaanxi Province. Meanwhile, the local spatial autocorrelation index measures the spatial heterogeneity of each element on the local scale. The Getis-Ord Gi* index is utilized to gauge the clustering of high and low values of carbon storage in local space and reveal cold and hot spots in spatial distribution [48].

2.3.5. Accuracy Analysis of Land-Use Simulation

In this study, the land-use situation in 2020 was simulated and cross-verified with the actual land use in 2020. The reliability of the simulation results was evaluated using the Kappa coefficient [49]. Verification of the simulation results yielded a Kappa value of 0.819 and an overall accuracy (OA) of 0.871, indicating the reliability and excellent performance of the model [48,50]. These results closely align with the verification findings of other scholars in related studies [51]. As a result, this model accurately projects future land use in Xi'an and provides a more accurate representation of land transformation.

3. Results

3.1. Space–Time Distribution of Land Use

3.1.1. Change in Land Use in Shaanxi from 2000 to 2020

Considerable changes have taken place in various types of land, as evidenced with Figures 3 and 4, from 2000 to 2020. The most significant changes occurred in construction land and arable land, while forestland and water areas were also impacted. The highest growth rate was in built-up land area due to economic development. Significant reduction in the area of cultivated land was as a result of the conversion of large amounts of cultivated land to forestland, construction land, etc. An increase in the area of forested land, grassland, and water areas exists with high ecosystem service value.

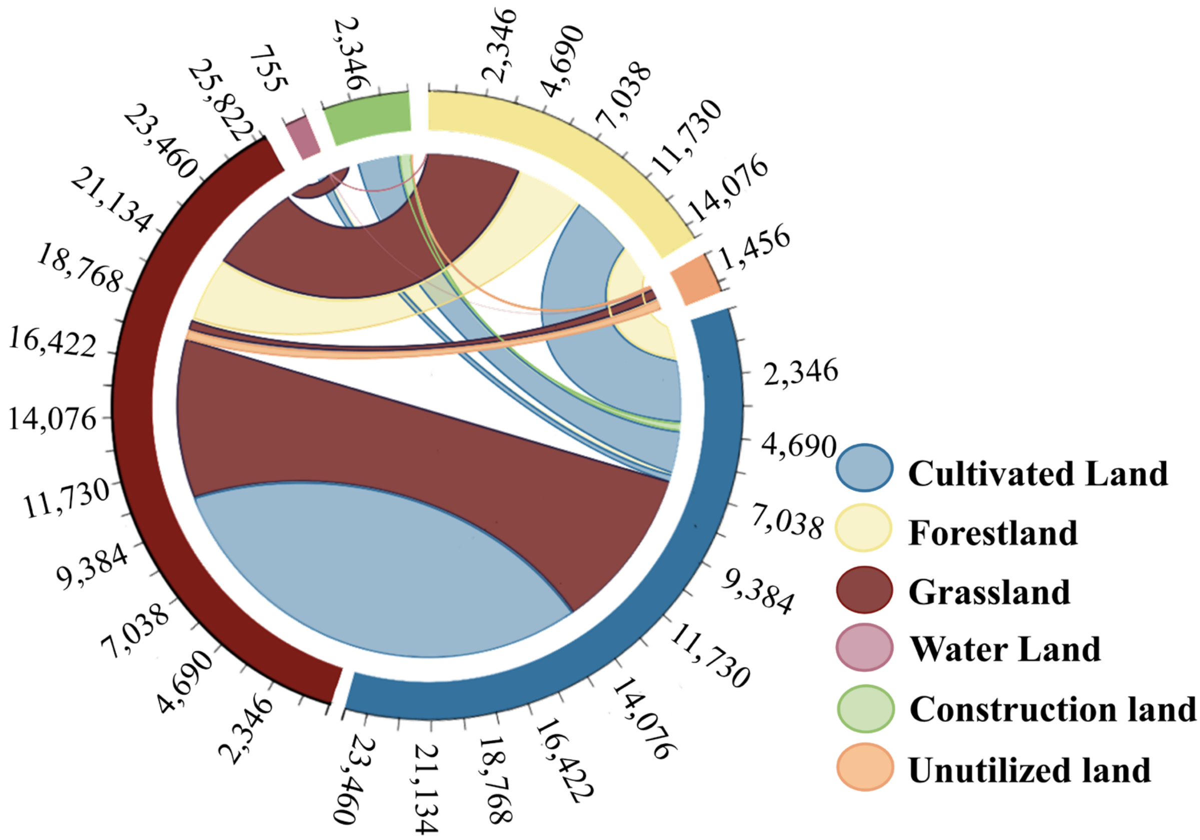


Figure 3. 2000–2020 Shaanxi land-use transfer quantity and chord diagram (km^2).

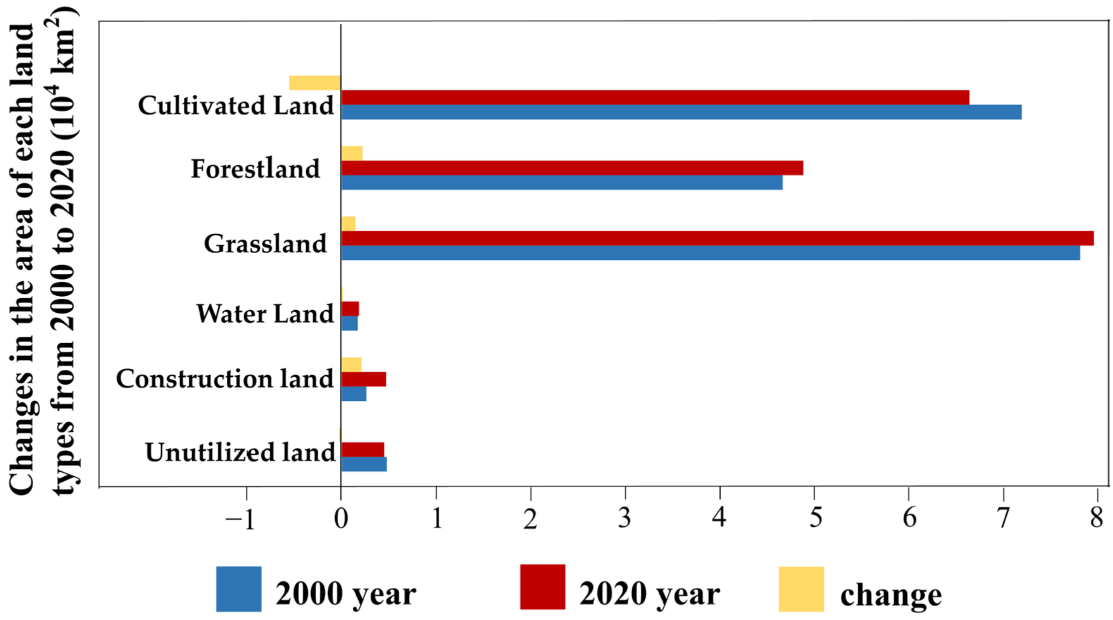


Figure 4. Changes in the area of each land type from 2000 to 2020 (10^4 km^2).

As shown in Figure 5, the spatial layout illustrates the land distribution in 2000 and 2020. The concentration of construction land is mainly seen in the Guanzhong Plain urban agglomeration, which attracts population and capital and, in turn, results in highly concentrated economic growth. However, less than one-third of the total land area houses 61.97% of the population and produces 80.83% of the GDP. Due to massive land development, ecological space has been dramatically reduced, significantly impacting cultivated, forested, and grassland areas.

3.1.2. Land-Use Patterns in Different Scenarios

Based on the forecast results presented in Table 2, it can be observed that the cultivated land area in Shaanxi is projected to exhibit a consistent downward trend in the future under the BUS. Conversely, there is an expected gradual increase in forestland, water area, and construction land. Meanwhile, the grassland area exhibits a pattern of growth followed by a decline. The transformation of 14,067 square kilometers of cultivated land into construction land and forestland highlights the neglect of ecological protection under the BUS. This expansion of construction land continually encroaches upon agricultural and ecological space, with the most significant impacts found in peripheral areas of cities and towns. Specifically, Xi'an, Xianyang, and Weinan are projected to undergo significant spatial changes. The simulation indicates that cities and towns are expanding, with numerous ecological lands being overtaken within city limits.

Table 2. Changes in the land-use area under different scenarios from 2020 to 2060.

Land-Use Type	Land-Use Area Change from 2020 to 2030/%				Land-Use Area Change from 2030 to 2060/%				Land-Use Area Change from 2020 to 2060/%			
	BUS	EPS	WEF	RRS	BUS	EPS	WEF	RRS	BUS	EPS	WEF	RRS
Cultivated Land	−7.01	−15.18	−5.85	−8.53	−5.41	−7.29	−3.51	−6.17	−12.04	−21.36	−9.15	−14.17
Forestland	1.20	3.28	3.14	3.55	1.73	1.28	0.74	0.91	2.95	4.60	3.91	4.49
Grassland	0.10	9.96	2.88	3.96	−0.59	3.39	1.01	1.98	−0.49	13.69	3.92	6.02
Water Land	1.49	−8.51	13.14	2.33	3.68	17.82	19.10	24.42	5.23	7.80	34.76	27.32
Construction Land	78.13	10.70	−5.18	9.00	29.44	1.70	9.31	19.05	130.6	12.58	3.65	29.76
Unutilized Land	−4.54	−9.31	−10.07	−7.31	5.01	−0.02	−0.86	3.14	0.25	−9.33	−10.85	−4.40

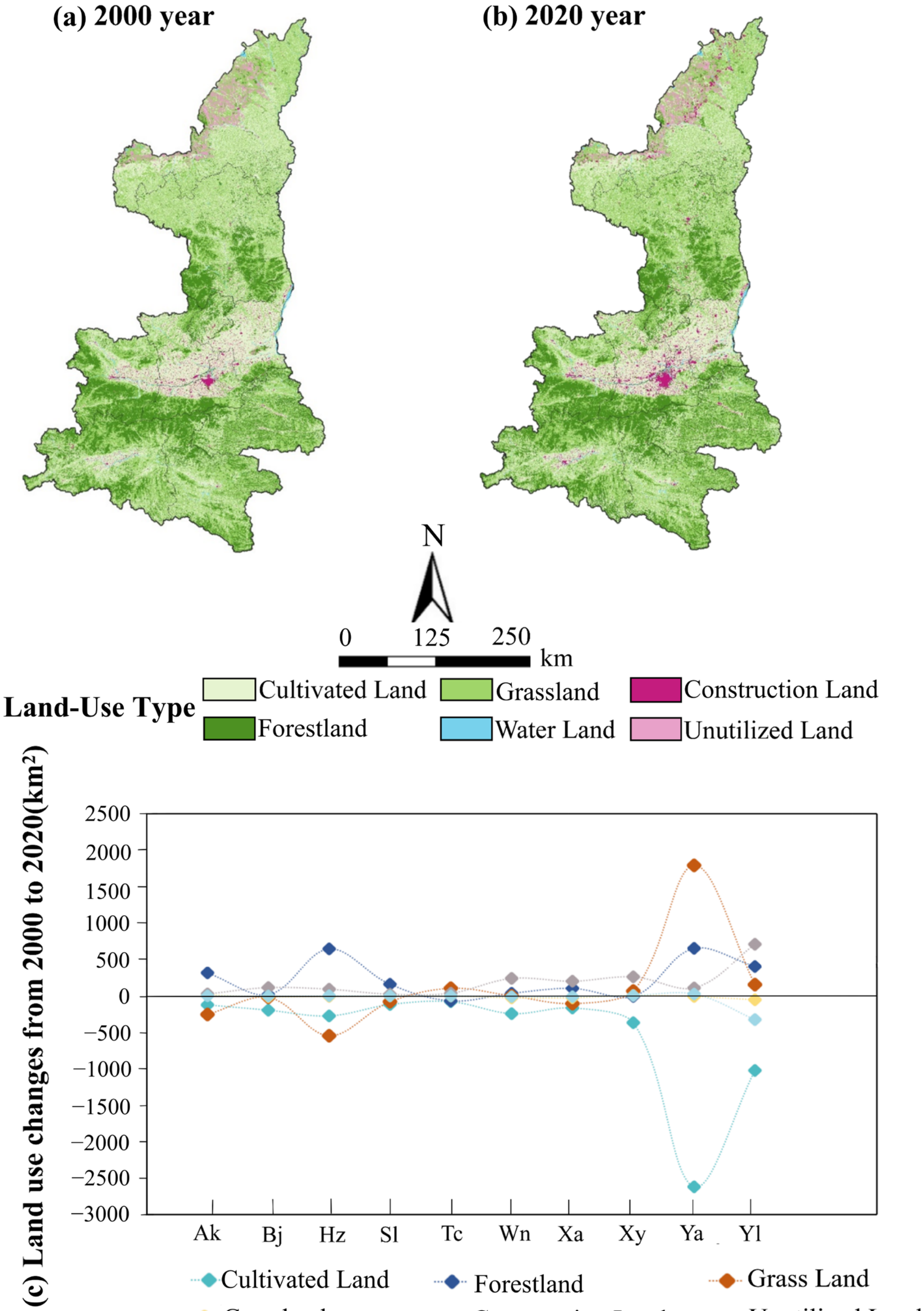


Figure 5. (**a**,**b**) Distribution map of land use in Shaanxi in 2000 and 2020; (**c**) The line graph depicts the land-use changes in various cities of Shaanxi Province (Ankang, Baoji, Hanzhong, Shangluo, Tongchuan, Weinan, Xi'an, Xianyang, Yan'an, and Yulin) from 2000 to 2020.

Under the EPS, there is a gradual decrease in cultivated land, resulting in an overall decrease of 21.3%. The scenario shows a consistent increasing trend in the area of forestland, grassland, water, and construction land from 2020 to 2030 and 2060. Notably, both forest and grassland areas are mainly sourced from previously cultivated land.

Under the WEF, there is a continued decrease in cultivated land from 2020 to 2030 and 2060, with a total reduction of approximately 9.1%. However, there is a simultaneous increase in the area of forestland, grassland, and construction land. Specifically, the water area has experienced a significant increase, with an overall rise of 34.76%. From the perspective of resource transfer, some of the newly developed construction land is transformed into grassland, forestland, construction land, and water. Additionally, this scenario experiences a minor reduction in the area of cultivated land compared to the other scenarios.

Under the RRS, there is a sustained decrease in the area of cultivated land from 2020 through 2030 to 2060. Conversely, there is an insignificant overall change in unutilized land, exhibiting a trend of initially decreasing and then increasing. Furthermore, there is a notable increase in the area of forestland, grassland, water, and construction land.

According to Figure 6, the BUS results in significant outward expansion of construction land areas. Construction land comprises large portions of cultivated land and surrounding forestland and grassland in the agricultural area of the Guanzhong Plain. Meanwhile, the EPS maintains a relatively stable land-use layout. The forestland and grassland areas increase in the Loess tableland area in central and southern Shaanxi. Under the WEF, construction land exhibits a gradual agglomeration trend and becomes more similar to the watershed area in 2060 than that in 2030. The cultivated land is mainly distributed in the agricultural production area in central Shaanxi and occupies a significantly larger area than in other scenarios. Ultimately, under the RRS, the construction of land changes significantly. Construction land is primarily distributed in urban areas in central Shaanxi and shows a gradual concentration trend, while other land-use distribution patterns remain unchanged.

3.2. Spatiotemporal Variation Characteristics of Carbon Storage

3.2.1. Spatiotemporal Variation Characteristics from 2000 to 2020

The examination of the relationship between land use and carbon storage, along with the analysis of the temporal and spatial distribution of carbon storage, is crucial for achieving regional carbon balance. Land use significantly impacts the level of carbon storage, making it essential to understand this relationship thoroughly. By understanding how different land-use patterns influence carbon storage, effective strategies can be developed to manage land resources and promote carbon sequestration, ultimately contributing to regional carbon balance initiatives.

Table 3 presents the reduction in carbon storage resulting from land conversion in Shaanxi Province. Table 3 shows carbon storage due to land conversion in Shaanxi Province between 2000 and 2020. Furthermore, Figure 7 highlights the distribution maps of carbon storage in 2000 and 2020, indicating that spatiotemporal carbon storage remained consistent. The Qinba Mountains in southern Shaanxi and the Loess Plateau in Central Shaanxi are rich in vegetation and have high carbon storage. Conversely, the urban district of the Guanzhong Plain and the windproof and sand-suppressing district in northern Shaanxi have relatively low carbon storage due to insufficient vegetation.

Table 3. Land-use and carbon storge change matrix from 2000 to 2020 (Mg C).

2000 Year	2020 Year						
	Cultivated Land	**Forestland**	**Grassland**	**Water Land**	**Construction Land**	**Unutilized Land**	**Sum**
Cultivated Land	/	40,888.29	41,574.42	−6275.78	−41,858.18	−2137.05	32,191.71
Forestland	−21,249.20	/	−34,004.85	−913.06	−2907.74	−2437.58	−61,512.43
Grassland	−29,713.53	45,201.81	/	−2992.56	−13,177.52	−10,246.33	−10,928.12
Water Land	3670.00	736.20	2789.23	/	−1.95	16.19	7209.67
Construction Land	9497.12	1121.93	1522.51	0.96	/	1.49	12,144.01
Unutilized Land	4346.00	1303.10	10,957.50	−37.01	−345.15	/	16,224.44
Sum	−33,449.60	89,251.33	22,838.81	−10,217.45	−58,290.53	−14,803.28	−4670.72

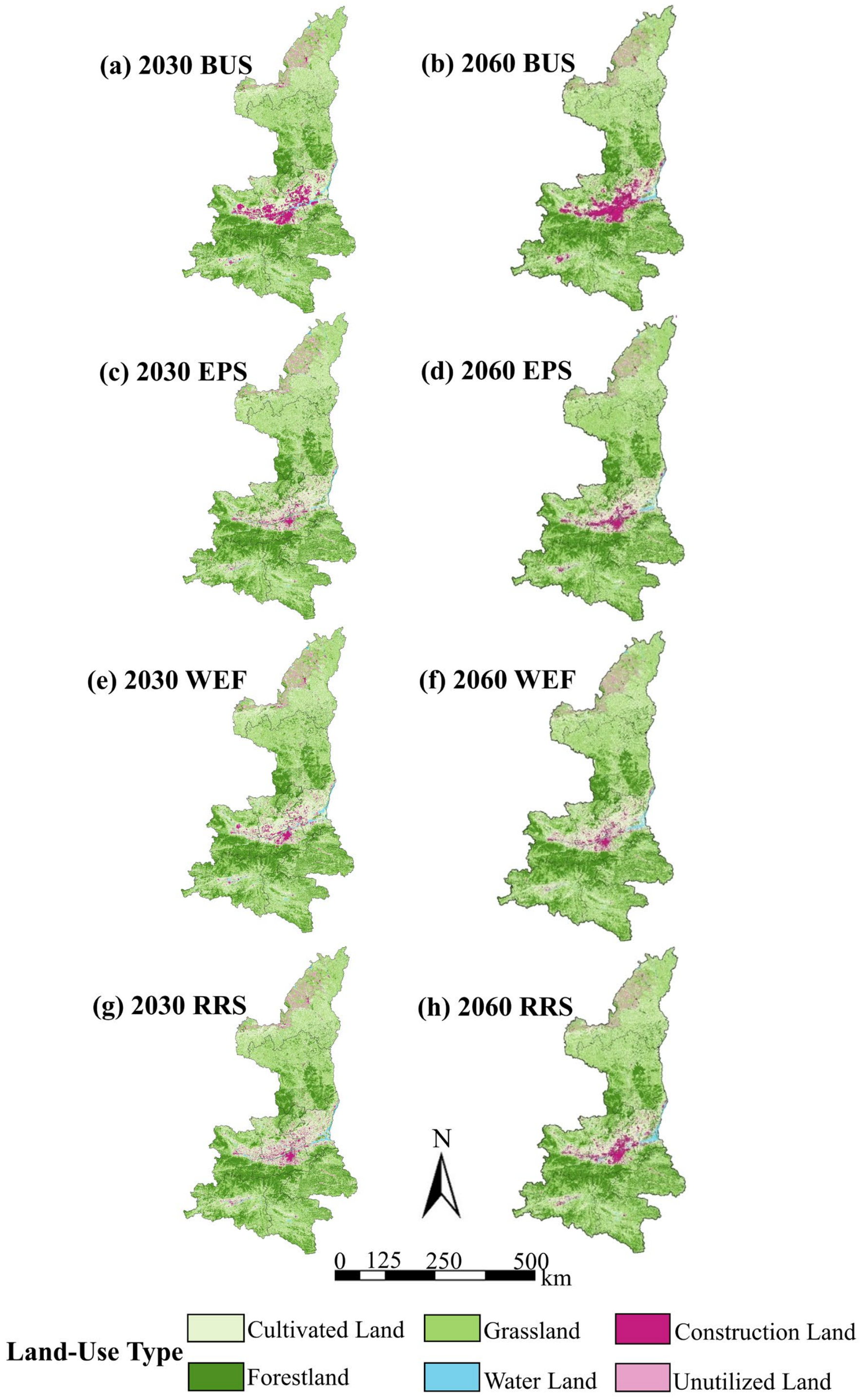


Figure 6. *Cont.*

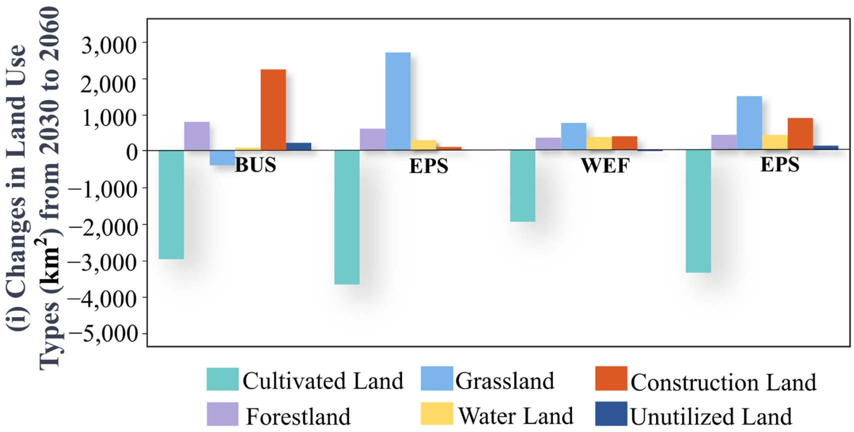
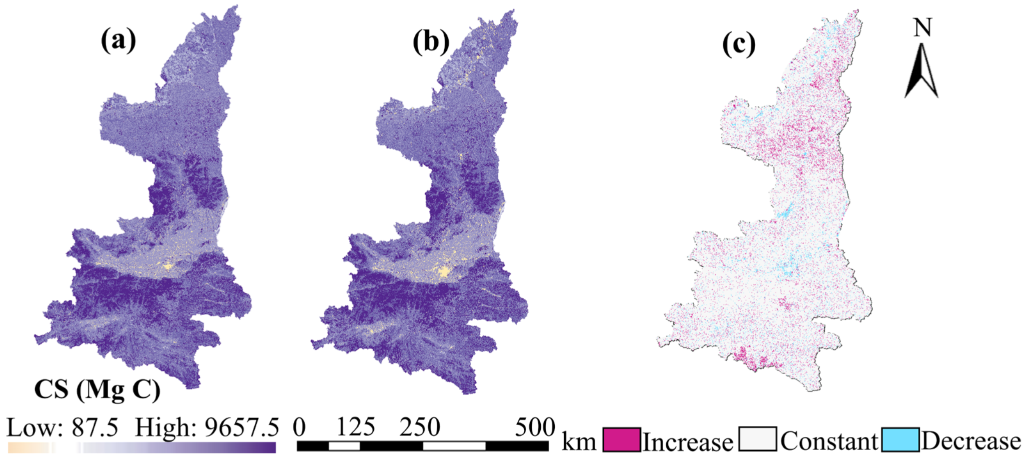


Figure 6. Time–space distribution of land use in Shaanxi in 2030 and 2060 under different situations (**a**–**h**); (**i**) the histogram and its data table show the changes of land-use types from 2030 to 2060.



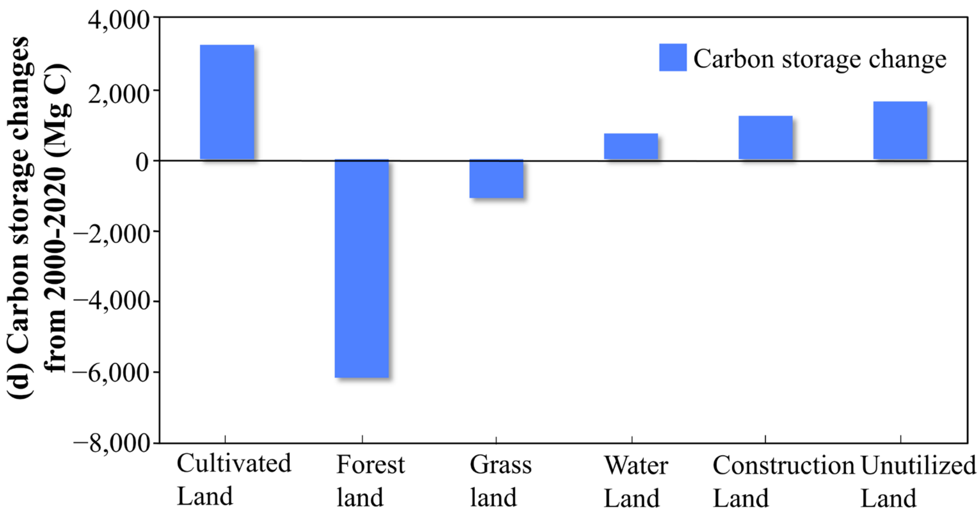


Figure 7. (**a**) is the distribution of carbon reserves in Shaanxi Province in 2000; (**b**) is the distribution of carbon reserves in 2020; (**c**) is the change and distribution of carbon storage from 2000 to 2020; (**d**) the histogram illustrates the carbon storage changes of various land types of Shaanxi Province from 2000 to 2020.

Significant changes in carbon storage from 2000 to 2020 occurred in urban land expansion areas, ecological preserves, and agricultural and grassland ecosystems. In the carbon storage reduction area, the reduction mainly occurred in the region spreading from the center of Xi'an to the surrounding areas. This area includes Yanta, Weiyang, Xincheng, Baqiao, Gaoling, northern Chang'an, part of Lintong, north-central HuYi, and northwestern Yanliang within Xi'an. In addition, carbon storage reduction occurred in Qindu, Weicheng, Yangling, and northeastern Xunyi Counties within Xianyang, southwestern Yan'an, northwestern Tongchuan, and the junction of Huangling and Yijun Counties. Other cities also had some areas with carbon storage reduction. Over the past 20 years, Shaanxi has focused on developing and building small- and medium-sized towns and accelerating urbanization. This process has led to the construction of the Xi'an metropolitan group at the heart of the Guanzhong Urban Agglomeration. Urban expansion has significantly reduced carbon storage by taking up much of the arable land. Areas with increased carbon storage are scattered in Yan'an City, Yulin City, and the southern part of Zhenba County, Ankang City, and Ziyang County in Hanzhong. The primary factor contributing to the increase in carbon storage in these areas is the growing emphasis on environmental protection in Shaanxi. Additionally, the favorable conditions of the Guanzhong Plain, characterized by its flat terrain and abundant precipitation, enable successful ecological restoration efforts.

3.2.2. Carbon Storage Forecast under Different Scenarios

According to Figure 8, from 2000 to 2030 and then to 2060, Shaanxi's carbon storage will show a continuous downward trend. The carbon storage of the BUS is the only reduction scenario among the four scenarios. This is because of the massive expansion of construction land to occupy carbon-intensive forestland and grassland, which poses a significant challenge to carbon sequestration and storage. In general, this scenario must limit the excessive growth of built-up land and increase forests and grasslands.

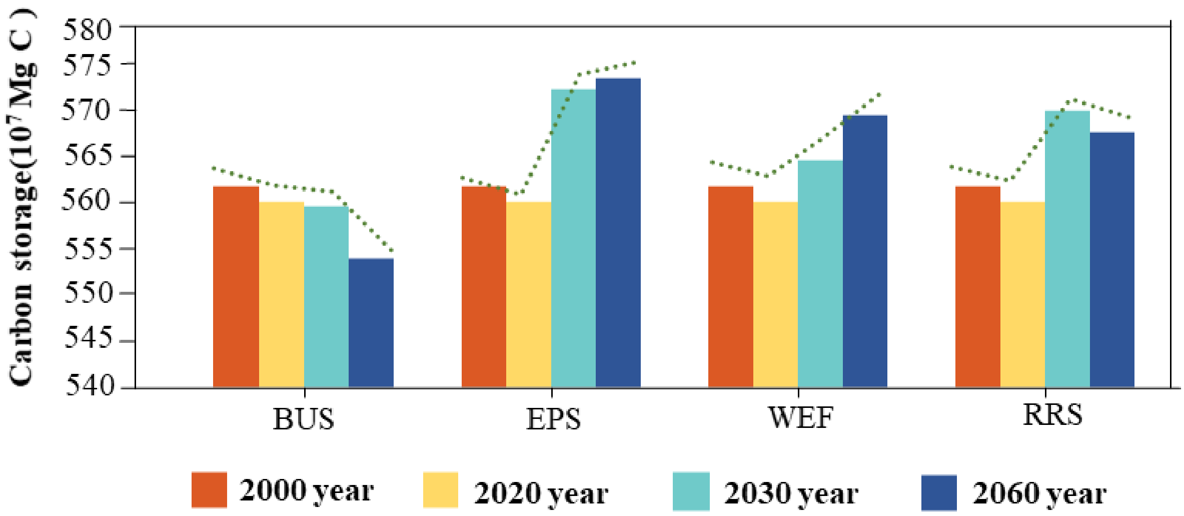


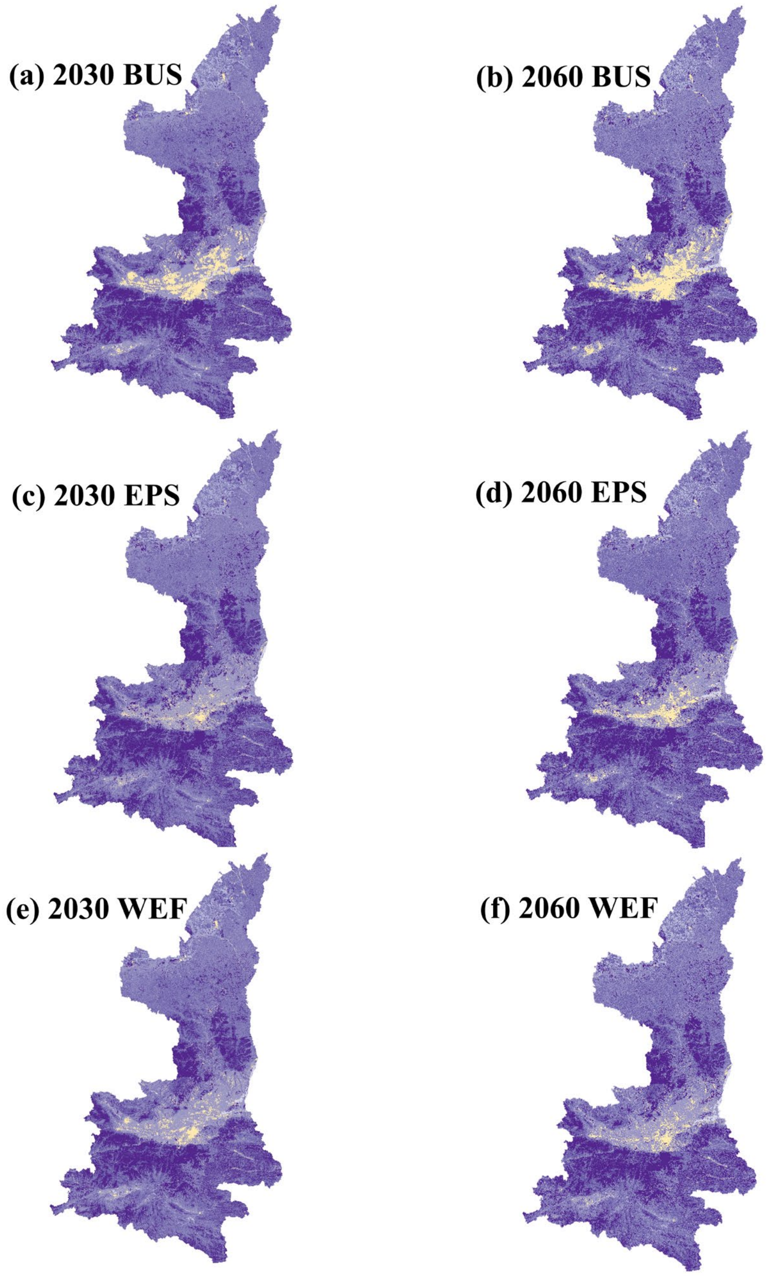
Figure 8. Histogram of carbon storage in different scenarios in each year.

Under the EPS, from 2020 to 2030 and then to 2060, Shaanxi's carbon storage will show a growing trend and the largest growth rate. The carbon storage in this scenario is significantly higher than that in the BUS. Moreover, the EPS has the highest carbon storage appreciation among the four scenarios. Under the WEF, Shaanxi Province's future carbon storage will also be on a growing trend. Under this scenario, carbon storage tends to increase year by year. Under the RRS, the overall trend of carbon storage in Shaanxi is increasing and then decreasing. The increase in construction land area under this scenario is the largest except for that under the BUS.

The spatiotemporal distribution pattern of Shaanxi Province has remained consistent throughout the years, with the Qinba Mountains and central Shaanxi serving as high-carbon sink areas where numerous forestlands and grasslands remain preserved. The implementation of different urbanization strategies yields varied outcomes on the province's carbon density. Based on Figure 9, the carbon storage quantity and spatial distribution under different land-use scenarios can be understood. The BUS shows a rapid expansion of the urban agglomeration centered on Xi'an, leading to a significant increase in construction land at the expense of agricultural and ecological space. This results in a sharp decrease in the region's average carbon density. In contrast, the EPS aims to promote ecological sustainability and, as a result, significantly raises the average carbon density in regions such as Jingyang, Ganxian, Liquan, Chunhua, Chengcheng, and Baishui. Carbon density outside Guanzhong also rises under this scenario. Conversely, the WEF shows a decline in the average carbon density of the Dali and Huayin Districts due to an increase in water areas. Meanwhile, the conversion of grasslands to forestlands in Yijun, Xunyi, Chunhua, Heyang, Chengcheng, and Huangling Districts leads to an increase in the region's average carbon density. Finally, the RRS exhibits the orderly development of Weihe River towns, resulting in a reasonable expansion of construction land. However, continued economic development leads to a decrease in the region's average carbon density.

The paper presents the spatial Moran's I values for carbon storage under different future scenarios, illustrating their clustering tendencies in Shaanxi Province. As depicted in Figure 10, the sample points mainly fall in the first and third quadrants, indicating significant clustering of carbon storage in this region. A hotspot analysis shows that there is little difference in the clustering distribution of high and low carbon storage values in 2030 and 2060 under various scenarios: BUS, EPS, WEF, and RRS (Figure 11a–h). Notably, the hotspots of carbon storage occur mostly in the southern Yan'an, northern Tongchuan, southern Baoji, and southern Xi'an regions. These areas are characterized by high vegetation coverage and concentrated ecological land. For example, Yan'an is a primarily agricultural district with extensive cultivated lands, while Baoji and Xi'an are primarily located within the Qinling Mountains in the south and southeast, both with high vegetation coverages. On the other hand, the carbon cold spots are mostly in the Guanzhong Plain's townships, agricultural ecological function areas, and ecologically fragile areas in northern Shaanxi. The area of the Guanzhong Plain covers mostly the central counties of Weinan, Xi'an, Xianyang, and Baoji. Moreover, part of northern Shaanxi comprises northern Yuyang District, northwestern Shenmu County and Hengshan County, southwestern Yuyang District, eastern Jingbian County, northwestern Jingbian County, and northeastern Dingbian County.

The data were processed using ArcGIS to extract and generalize the stable zones where carbon storage remains largely unchanged under the four scenarios and the unstable zones where changes are prone to occur. According to Figure 11i, the unstable areas more prone to carbon storage variations in the future are mainly concentrated in the agricultural and urban areas of the Guanzhong Plain. In contrast, the Qinling areas and the gully areas of the Loess Plateau are stable areas where carbon storage is less susceptible to influence.



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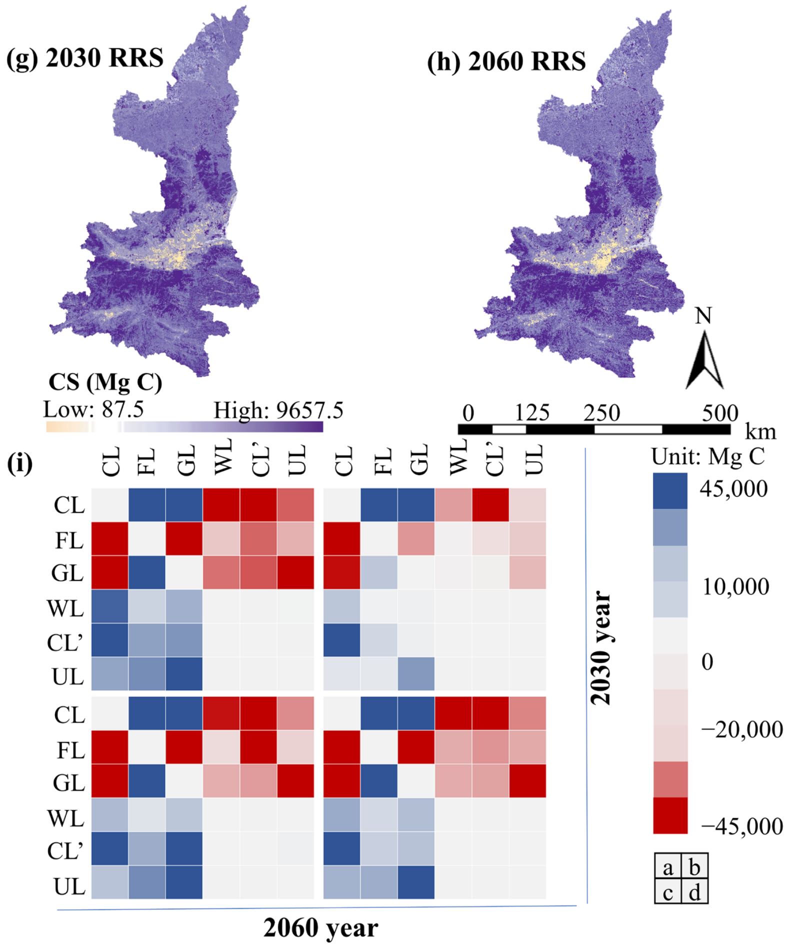

Figure 9. (**a**–**h**) Carbon storage distribution in 2030 and 2060 under different scenarios; (**i**) carbon storage transition heatmap: carbon storage changes resulting from land-use transitions from 2030 to 2060. As indicated in the legend in the bottom right corner, a represents BUS, b represents EPS, c represents WEF, and d represents RRS (CL: Cultivated Land; FL: Forestland; GL: Grassland; WL: Water Land; CL′: Construction Land; UL: Unutilized Land).

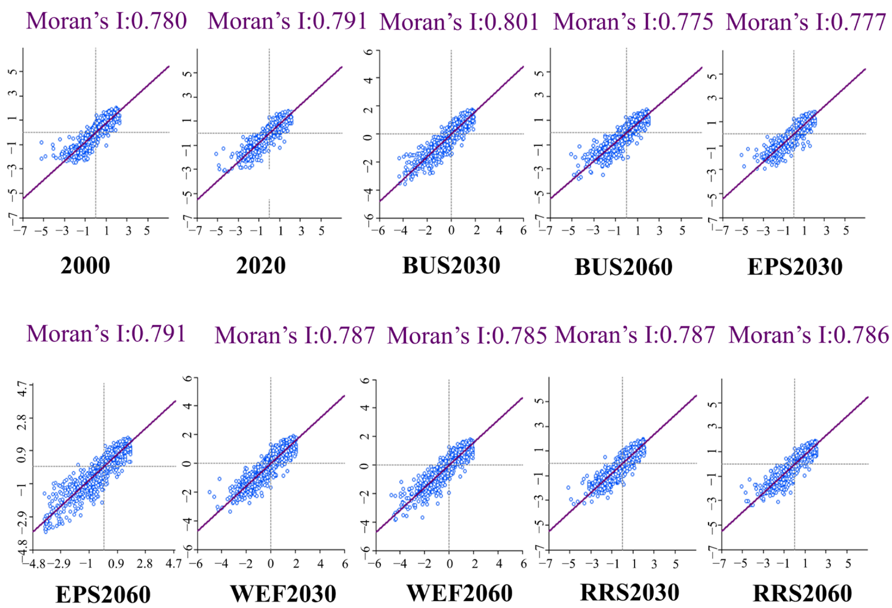

Figure 10. Moran's I scatter plot of carbon storage distribution under four scenarios in different years.

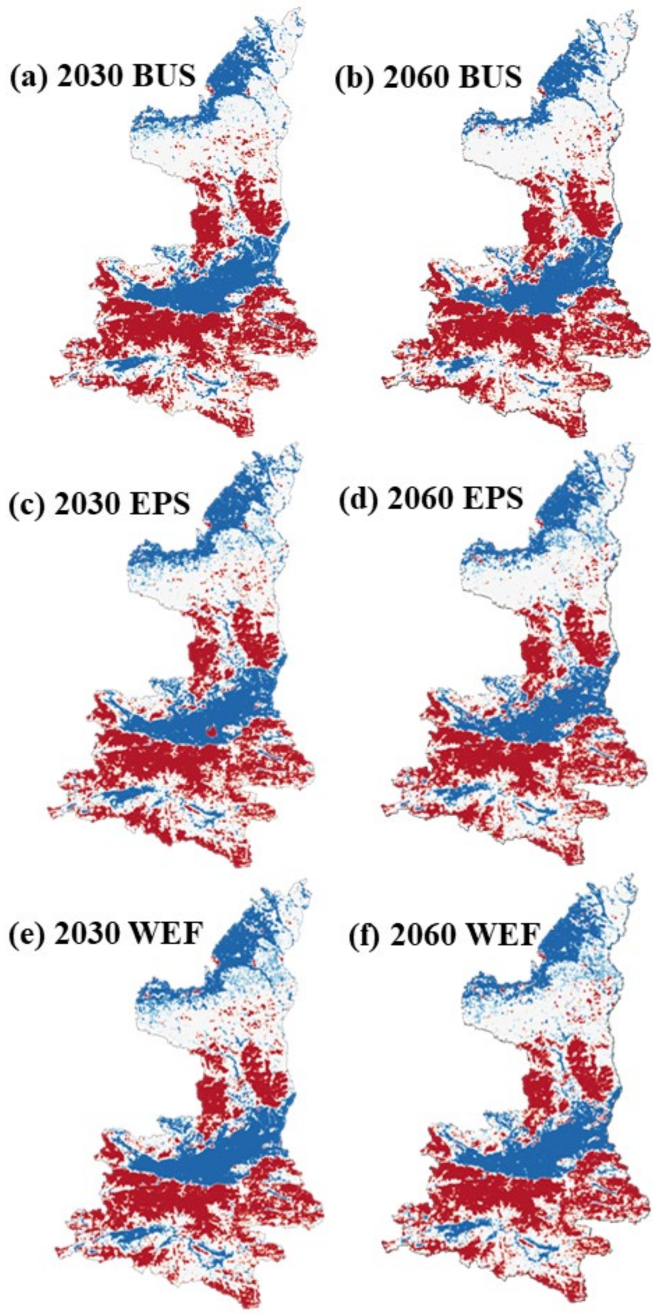

Figure 11. *Cont*.

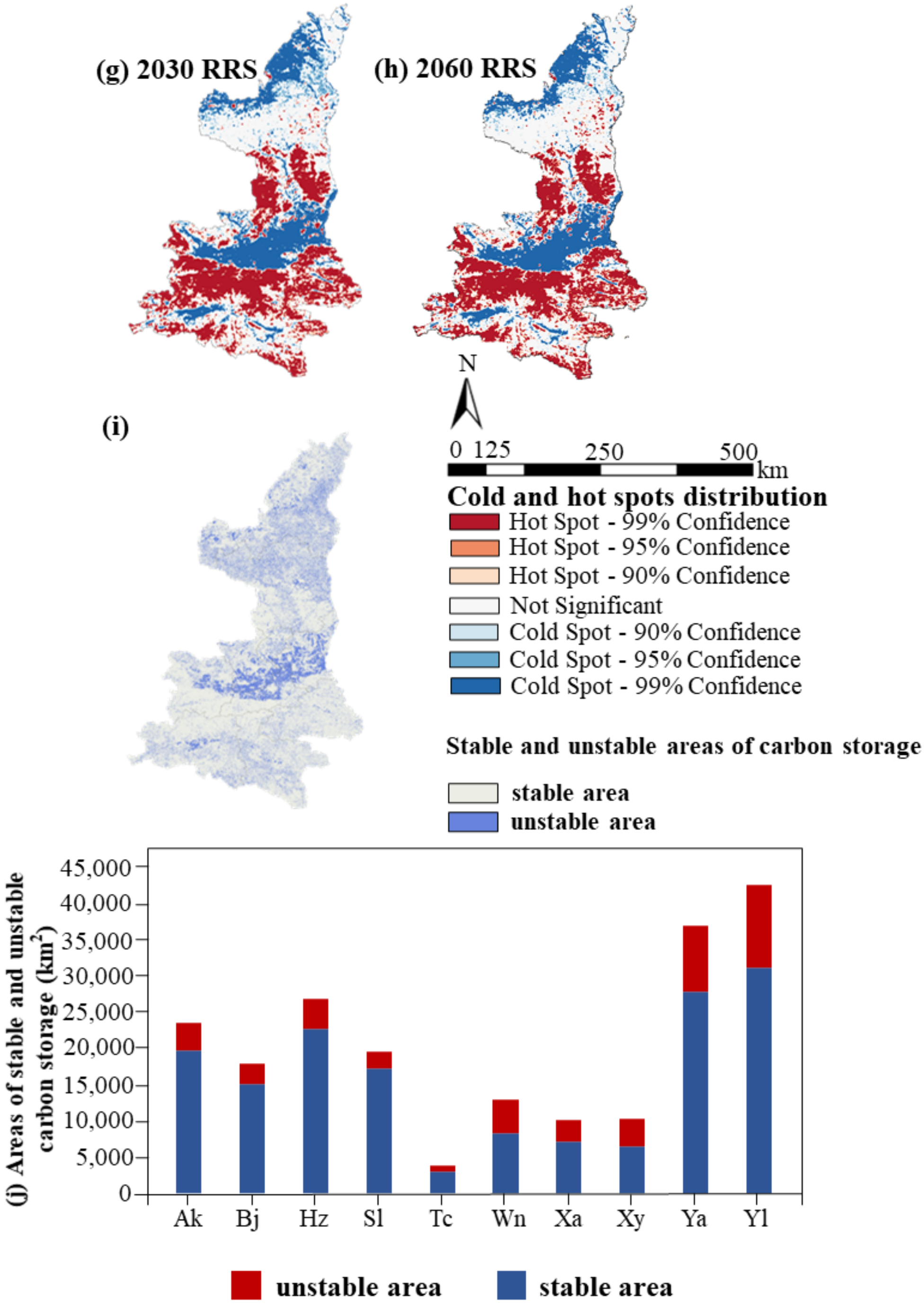

Figure 11. (**a**–**h**) Distribution of carbon storage hot and cold spots under different scenarios in 2030 and 2060; (**i**) stable and unstable areas of future carbon storage changes; (**j**) the stacked bar chart represents the areas of stable and unstable carbon storage in the cities of Shaanxi Province (Ankang, Baoji, Hanzhong, Shangluo, Tongchuan, Weinan, Xi'an, Xianyang, Yan'an, and Yulin).

4. Discussion

4.1. Relationship between Carbon Storage and Land-Use Change

Terrestrial ecosystems play a critical role in global carbon storage [52]. Various factors affect carbon storage in ecosystems [53,54], and land use is a crucial one [55,56]. Many land-use strategies can increase carbon sequestration in ecosystems [57,58]. The development of appropriate land-use plans is essential for expanding regional carbon storage, enhancing regional carbon uptake ability, and achieving a balanced regional carbon budget.

This study analyzed the response of carbon storage to land-use change in the past. Furthermore, the study simulated the spatial and temporal distributions of carbon storage under four different scenarios, thereby offering a foundation for policy formulation. The analysis indicates that in the past, carbon reserves in Shaanxi generally exhibited a declining trend. However, in the last decade, it is evident that the rate of decline significantly slowed down. These findings align with the trends observed in other relevant studies [59]. The development of construction land involves topsoil stripping and soil compaction, leading to a decrease in vegetation and soil carbon density [60]. The disorderly expansion of construction land before 2010 led to the decrease in regional carbon storage. Regrettably, new construction land usually occupies flat and high-quality arable land [32], leading to a reduction in the value of ecosystem services (ESV) and increasing the risk of food shortages. In the past decade, Shaanxi Province has implemented several environmental protection measures, such as the Grain for Green Project, which aims to restore degraded land to forest and grassland and increase the area of water bodies. The ecological restoration and protection projects in Shaanxi Province have been the main contributors to mitigating the reduction in carbon storage. This finding suggests that the implementation of ecological conservation measures can effectively enhance regional carbon storage, which aligns with the conclusions of other researchers. For instance, Zhang et al. conducted a study examining the influence of rapid urbanization on carbon storage. The study highlighted the importance of increasing vegetation coverage in urban areas [61]. They also suggested exploring the potential for green vegetation to replace public spaces such as parking lots [62]. The results indicate that ecological engineering can improve regional carbon storage. Nogueira and other authors have pointed out that carbon loss in the Amazon Basin is mainly due to tropical forest vegetation loss. Protected areas play a crucial role in conserving the ecological environment and mitigating climate change [63]. High-carbon-storage areas in Shaanxi Province are found in regions characterized by abundant vegetation and high ecological environmental quality, whereas low-carbon-storage areas are typically located in urban areas and ecologically fragile regions, such as sandy areas. Over the past decade, Shaanxi has gradually prioritized protecting the Qinling Mountains and the Yellow River Basin, implementing policies of returning farmland to forest and grassland, and thus maintaining regional ecological stability.

Focusing on the future is vital, as we face several challenges in achieving sustainable development and protecting the regional ecology. To address the current dilemmas, we propose four projection scenarios. These scenarios will provide a basis for land planning and carbon balance for the future in this region, considering its conditions and future development direction. Based on the identified stable and unstable carbon storage areas under the four future scenarios, it is evident that the most concentrated changes will occur in the rapidly developing urban areas of the Guanzhong Plain. Conversely, the most concentrated areas that are less susceptible to change are the protected regions of the Qinling Mountains. Among them, BUS reflected the same development trend over the past 20 years. Unfortunately, this scenario also signifies the rapid outward expansion of construction land that releases significant amounts of carbon and leads to a decline in carbon storage [64]. Consequently, it warns us of the need to limit excessive construction land growth and underscores how ecological environmental sustainability must not be ignored in the national development strategy. The substantial increase in carbon storage under the EPS can be attributed to the extensive conversion of cultivated land into forest and grassland. This achievement is realized through the implementation of ecological protection measures, such as the designation of key ecological function areas and ecologically sensitive areas, as well as the execution of ecological projects. The application of ecological engineering techniques contributes to the enhancement of carbon density, biodiversity, and a consequent increase in carbon storage [65,66]. Concurrently, restricting the transfer of forestland and grassland leads to an increase in their quantity, thereby positively impacting carbon sequestration and storage. These results demonstrate the efficiency of ecological protection in achieving regional carbon balance [67,68]. However, the EPS occupies a considerable amount of cultivated land, potentially jeopardizing its ability to meet future food security needs. The WEF integrates water resource utilization, food security, and ecological protection. The approach prioritizes the protection of water bodies, cultivated land, and ecological land, resulting in a significant increase in carbon reserves and minimizing the loss of construction land. Through this protection, the ESV in water areas and other ecological spaces will improve [69] along with the ecological environment. The plan promotes carbon storage growth while mitigating the damage to key resources. The RRS considers construction land demand, ecological space, and food security for rural revitalization. The scenario reserves an area for the expansion of construction land for this purpose while simultaneously emphasizing ecological land protection and ensuring high-quality ecological background resources. Protecting cultivated land resources and limiting cultivated land reduction are also emphasized to promote ecological and industrial development. The RRS positively impacts regional carbon reserves through these efforts. Generally, this scenario promotes an increase in regional carbon storage.

Of these four scenarios, the BUS is the one to be avoided. Under this scenario, the unregulated expansion of construction land will encroach on the surrounding ecological land with an ecological role and the agricultural land with a food production role. The WEF is the most likely scenario to be developed in the future because it can protect the ecological environment and promote high-quality development. This scenario is a good balance between economic and ecological needs and is worth exploring, as it can support the achievement of regional carbon neutrality through further planning.

4.2. Expectations and Strategies

The land-use patterns in Shaanxi Province should consider ecological protection, economic development, and land security simultaneously. To achieve economic, ecological, and food security, regulations that protect and develop high-quality farmland must be established and followed. Forests and grasslands have excellent carbon storage capacity [70] and are important in promoting carbon sequestration. Therefore, efforts should be made to enhance their roles as carbon sinks to promote the intensive use of forests and scientific management of economic forests and realize the carbon sequestration value of forests [71]. Grassland protection and development should also be emphasized to promote greening in Shaanxi. While ensuring land resources, in-depth research on agricultural management measures should be conducted and land carbon density should be increased [72]. Protecting ecosystem watersheds is the best way to provide valuable ecosystem services [73]; thus, protecting water resources is necessary. As an essential region of northwestern China, Shaanxi should plan for urban land demand to promote economic development. However, strict compliance with urban development boundaries is necessary to encourage effective and efficient land use. Furthermore, because urbanization levels are inversely proportional to carbon sequestration, the protection of high-grade ecological land and the reduction in new construction land are needed. Moreover, green building in urban areas should be promoted, and low-carbon and carbon-fixing buildings should be explored [74].

Land-use planning in Shaanxi should be tailored to local conditions due to the substantial variations in natural and economic factors across different regions. The internal land-use structure of Shaanxi should be optimized based on the four development scenarios explored in this study while considering the protection of ecological resources, ensuring food security, and taking into account the region's different development needs and spatial development layout. Based on the development results of these scenarios, this paper analyzed Shaanxi's internal division of labor from different angles. First, as a mega-city, Xi'an should limit the over-expansion of new construction, develop green infrastructure to reduce carbon emissions [75], and explore the development of urban landscapes that can enhance the carbon storage potential. Industrial transformation and upgrading should be accelerated, and the city's radiation capacity should be increased. General processing manufacturing should be guided towards small- and medium-sized cities in surrounding areas to enhance urban land-use efficiency. In rural areas, industrial development should be accelerated, and infrastructure improved, while promoting rural revitalization and economic development and protecting the ecological environment. For areas with important ecological functions, development plans similar to EPS should be considered to strictly protect key regions and limit large-scale development activities in surrounding areas.

BUS needs careful consideration. In this case, the disorderly expansion of construction land will encroach on the surrounding ecological land and agricultural land that has a vital function in food production. WEF is a valuable and feasible scheme for the future, as it can protect the ecological environment and promote high-quality development. This scheme provides a good balance between economic and ecological needs that can be supported with further planning to achieve regional carbon neutrality.

The landscape pattern of Shaanxi Province is characterized by uneven distribution of landscape elements and uneven economic development within the region. Guanzhong is in a leading position, northern Shaanxi has economic development potential, and southern Shaanxi has the weakest level. From the perspective of ecological protection, southern Shaanxi has the highest ecological service capacity. Northern Shaanxi is characterized by ecological fragility and needs to focus on protection. Guanzhong can guide the development of eco-agriculture and promote ecological security and agricultural development. The planning and optimization of the landscape pattern needs to take into account relevant factors such as nature, population, and industry in an integrated manner, and coordinate all aspects such as water, carbon, and soil. In our future research, we will deeply analyze and quantify the current situation of the landscape pattern in Shaanxi Province. We will also propose spatial pattern optimization strategies in terms of driving factors, ecological construction, and integrated development of water–carbon–energy–food in the study area.

4.3. Uncertainties and Limitations

This study employs a combination of the PLUS model and InVEST model to forecast the future distribution patterns of carbon reserves under different land-use scenarios. The method provides a more systematic and scientific approach for the long-term development of carbon reserves in Shaanxi Province. However, the method has a few limitations that need to be addressed.

The PLUS model integrates socioeconomic, climate, and environmental data to generate probabilities for different land-use types. It is a reliable tool for accurately simulating land-use changes under various policy scenarios. However, analyzing land-use changes requires comprehensive studies of population, economy, temperature, precipitation, and other factors due to the complex and dynamic nature of the process. The simplification of the InVEST model algorithm affects calculation accuracy to some extent by overlooking crucial indicators for carbon sequestration, such as the photosynthetic rate and soil microbial activity, which leads to a certain error in carbon storage. Future research can enhance the accuracy of the models by integrating simulation techniques that incorporate more comprehensive parameters, allowing for better control of variables. This approach would lead to improved precision and reliability in the modeling process.

5. Conclusions

The LP-PLUS-InVEST model is utilized to optimize the land-use structure and carbon storage based on data from Shaanxi Province spanning 2000 to 2020. The research aims to provide theoretical support and methods for developing land-use policies. The outcomes of the research are as follows:

Based on quantitative findings, carbon storage in Shaanxi Province has exhibited a declining trend over the past two decades. This decrease is primarily attributed to the expansion of construction land, which has had the most significant impact. The increase in carbon storage from forestland and grassland has proven inadequate in offsetting the decline caused by the substantial expansion of construction land. Furthermore, the findings indicate that carbon storage exhibits distinct spatiotemporal distribution characteristics. The carbon density is lower in the urban group surrounding Xi'an on the Guanzhong

Plain, while it is higher in southern Shaanxi's mountainous area and the Loess gully area of Guanzhong.

The overall carbon storage exhibited a significant decrease under the BUS. Among the four scenarios considered, only the BUS showed a reduction in carbon storage. On the other hand, the EPS exhibited a substantial increase in carbon storage, which was the highest compared to the other three scenarios. The overall carbon storage also increased significantly under the WEF. In the RRS, carbon storage increased significantly at first and then decreased slightly; increases in construction land are associated with decreases in carbon storage. The distribution of carbon reserves in Shaanxi Province exhibited a general consistency. The level of carbon storage was low in towns and cities located on the Guanzhong Plain and in the northernmost desert area. Conversely, the level of carbon storage was high in cultivated land and grassland found in northern Shaanxi. Additionally, the highest carbon storage was observed in the southern mountainous areas.

In summary, land-use structures should be adjusted appropriately based on primary conditions and development goals. The protection of ecological land is critical in high-ecological-value areas. The expansion of large cities should be controlled, and development plans must be reasonably formulated for rural town areas to promote economic development in those regions.

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