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Spatiotemporal Analysis of the Impacts of Land Use Change on Ecosystem Service Value: A Case from Guiyang, China

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Abstract: The significance of ecosystem services and land use for human well-being and sustainable development cannot be understated. Scientifically assessing the ecosystem service value (ESV) and studying the relationship between land use change and the ESV can provide a theoretical groundwork for land use planning and ecological administration in Guiyang. In this study, gradient analysis was utilized to explore the changes of ESV at district level of Guiyang. Then, the synergistic relationship and the strength of the interaction between land use intensity (LUI) and ESV were explored by using a coupled coordination model and spatial autocorrelation analysis. Furthermore, polynomial fitting was carried out for the LUI index and its linked coordination index in relation to the ESV. The results showed that (1) the areas of farmland, forest, grassland, and unused land in Guiyang decreased from 2000 to 2020, while the areas of construction land and water body increased conversely. (2) The expansion of the construction land and water body was the main cause of the ESV change pattern in Guiyang, which first moved downward and then upward. (3) The ESV and LUI had a low overall coupling coordination degree (CCD). Spatial autocorrelation studies showed that low–to–low aggregation and high–to–high aggregation dominated the spatial patterns of essential regions. (4) The LUI and CCD indexes exhibited an inverted U-shaped curve correlation.

Keywords: ecosystem service value; land use change; land use intensity; coupling coordination; polynomial fit

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1. Introduction

An ecosystem comprises living organisms and their surrounding conditions [1]. The products and services ecosystems offer people are known as ecosystem services. These services are categorized into four categories: providing, regulating, supporting, and cultural. Humans may derive direct or indirect benefits from the functions of an ecosystem [2,3]. Ecosystems impact economic growth and human welfare, and ecosystem changes may offer notable benefits to humans. Still, the accompanying costs involve the degradation of ecosystem services and an increase in their potential risks [4,5]. The rapid industrialization and urbanization, economic expansion, and extensive deterioration of ecosystems all strain ecosystems increasingly [6]. The concept of ecosystem service value has gained significance in addressing the challenges of ecosystem services more crucial [7]. As the LUI can alter notable elements of ecosystem functioning, including the conflicts between ecosystem functions and services, as well as their benefits, it is imperative to consider how the LUI impacts ecosystem services and functions [8]. The relationship between land use and ESV needs to be explored to improve human well-being and provide theoretical support for the creation of regional development policies on land use and ecosystem services.

ESV measurements are essential for social development [9,10] because they necessitate balancing several factors that impact the welfare of people in various circumstances in which decisions are made [11]. Since the 1990s, significant research has been conducted on the quantification of ESVs [12–14]. The financial ESV can be determined by comparing the relative values of various indicators and by measuring them in labor or time units [15]. Further research on expressing ESVs in monetary terms is warranted, as doing so would support decision making. Monetary valuation methods for ESV usually include ecological modeling, economic valuation methods based on unprocessed data, and value transfer methods based on land use in terms of unit values [16]. There are two steps involved in the primary estimation process: the first step is to quantify ecosystem services and processes with the use of ecological models (such as water conservation models) or indicators (such as land utilization) and then evaluate them using economic valuation methods [17–19]. Because these methods are computationally demanding and require many parameters, harmonizing and standardizing the assessment parameters for every ecosystem function is more challenging when methods that rely on unprocessed data are used. Consequently, these methods are suited for assessing ESV for specific services within a particular ecosystem or at small spatial scales [20]. The unit value technique calculates ESVs using the economic worth of a unit area inside a given environment. It is appropriate for large spatial scales and integrated ESV evaluations [21]. Costanza updated the worldwide ESV using data from an ESV database that De Groot created [7,22], which included the ESV for ten key biomes. In order to calculate the ESV in China based on prior research, Xie constructed an equivalency factor approach based on the unit value method and consulted 500 Chinese ecological specialists [23,24]. In China, the equivalency factor approach is frequently applied, particularly for research that assesses the ESV of land use change (LUC) [19].

Since terrestrial ecosystem services are susceptible to LUC, land use planning must consider these effects [25,26]. Scholars have demonstrated the relationship between LUC and ESV by analyzing how land use patterns can alter how ecosystem services are given [27,28]. LUC significantly affects the form and functions of significant ecological systems and ecosystem services and their values [29]. Ecological services and land use are influenced and constrained by each other [30]. The speed at which human society has developed has increased human influence on the natural environment, and this has caused environmental harm and underscored the vulnerability of ecosystems [31]. Research has shown that land degradation brought on by LUC may obstruct the delivery of ecosystem services in a particular location and impede the ability of ecosystems to develop sustainably [32,33]. Different land use types can provide various ecosystem services. For instance, farmland can provide more food than forest, but forest has higher carbon reserves and provides more services for the production of lumber [34]. Land use changes include modifications to the kinds of land utilized and adjustments to the intensity and spatial patterns of land usage [35]. In analyzing the connection between ecosystem services and LUC, more researchers have recently looked at variations in land use types [36–38]. For instance, environmental degradation and excessive human encroachment on ecological lands, such as wetland, grassland, and forest, are the reasons behind the decline in associated ecosystem services [27,39]. Proactive measures such as reforestation and tree planting improve some ecosystem functions [40,41]. Although the connection between LUI changes and ecosystem services has not received much attention [42], changes in LUI also affect the services and functions of ecosystems [43]. Xu [44] conducted a variance and correlation analysis to determine how LUI affected ecological services and human well-being. He discovered that the increasing LUI improved food production, soil conservation, and climate control. According to Chillo's [45] research on the effects of LUI on ecosystem functions, it can be observed that the indirect effects of LUI on ecosystems were of significant importance. Lucia's research indicated that while ecosystem services and ecosystem functions can be enhanced at moderate LUI levels. However, the positive correlation between ecosystem services and ecosystem functions decreased, at higher LUI levels [8].

Guiyang is a typical karst city in Southwest China, characterized by high fragmentation and heterogeneity in its landscape, as well as fragile ecosystems and ecological environments [46]. Due to the weak and unstable ecological restoration capacity of karst ecosystems, limited ecological carrying capacity, and the high ecological sensitivity, the ecological system of Guiyang City is easily influenced by external pressures [47]. Although there has been an overall improvement in ecological quality in Guiyang since the 1990s, primarily as a result of the implementation of national ecosystem restoration and other policy projects, the degradation of land still persists in the city center area, and the high rate of urbanization is associated with low environmental quality [48]. Guiyang, with its growing economic prosperity, is experiencing continuous urban expansion and damage to its fragile ecological environment. As LUC can alter notable elements of ecosystem functioning, including the conflicts and benefits between ecosystem functions and services, it is necessary to unveil how LUC influences ecosystem functions and services. However, few studies have concentrated on ESV changes in karst areas, and few have addressed the relationship between LUI and ESV. Karst areas have more fragile ecosystems and need to pay more attention to their land use–ecosystem relationship. Theoretical frameworks can be proposed for land use planning and ecological regulation in Guiyang by evaluating ESVs scientifically and examining the connection between LUC and ESV.

The coupled coordination model and polynomial fit were employed in this work to explore the patterns and changes in land use and ecosystem services in Guiyang, both spatially and temporally, from the standpoint of linking land use with ecosystem services. This model attempted to explain how urbanization has evolved with the relationship between land use and ecological services. The following are the goals of this study: (1) quantitative assessments of these variables in Guiyang in 2000, 2005, 2010, 2015, and 2020, as well as an assessment of the spatiotemporal distribution aspects of LUC and ESV; (2) assessment of the features of the temporal and spatial distributions of various forms of coupled coordination using the coupled coordination model to explore the connection between ecosystem services and land use; and (3) examination of the degree of coupled coordination in the LUI–ESV pattern of change, as well as the trend in the change between the two indicators and the possibility of a turning point in the change process.

2. Materials and Methods

2.1. Study Area

Guiyang (106°07′ E–107°17′ E; 26°11′ N–26°55′ N) is the provincial center of Guizhou Province and has a karst landscape. The city of Guiyang is located on a watershed that separates the tributaries of the Chishui River of the Pearl River system and the Wujiang River of the Yangtze River system. The jurisdiction of Guiyang includes six main urban areas and "one city and three counties", and its main urban areas include Nanming, Yunyan, Huaxi, Wudang, Guanshanhu, and Baiyun, and the "one city and three counties" refers to Qingzhen, Kaiyang, Xifeng, and Xiuwen (Figure 1). Different degrees of impact of increasing urbanization in Guiyang on the land use structure and ecological services have been observed. The years 2000, 2005, 2010, 2015, and 2020 were selected as study periods to expose changes in land use and the ESV of Guiyang. This study explained the changes in land use dynamics, LUI, and ESV in terms of space and time, explored the coupling and coordination of LUI and ESV, and provided references for ecological security and sustainable development in Guiyang.

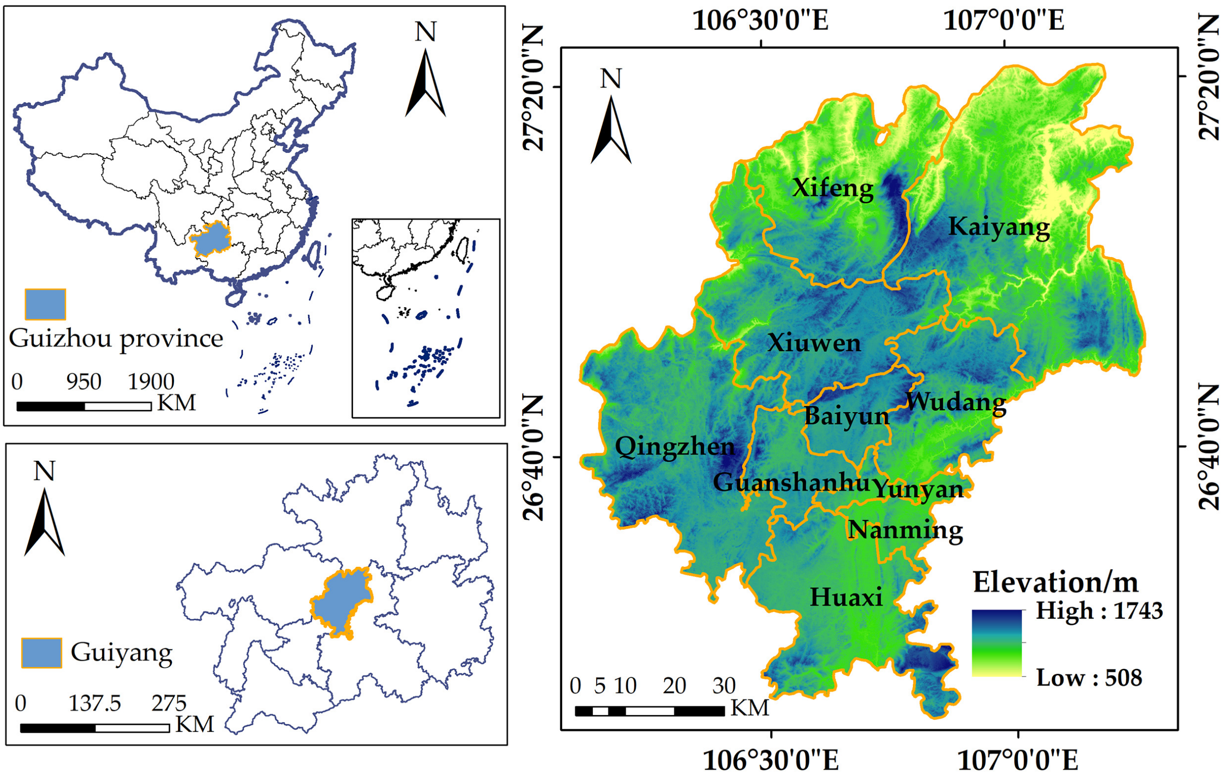

Figure 1. Location of Guiyang in China.

2.2. Data Sources

Land use data with a resolution of 30 m raster data was sourced from the Resource and Environment Science Data Center of the Chinese Academy of Sciences. Six primary categories exist for land use statistics: farmland, forest, grassland, water body, construction land, and unused land [49]. Digital elevation model data was acquired from the Geographic Data Spatial Cloud. Administrative divisions originated from the National Catalogue Service for Geographic Information. The area, production, and selling price of major grains in Guiyang were obtained from the Guizhou Statistical Yearbook, the Guiyang City Statistical Yearbook, and the National Compilation of Information on Costs and Benefits of Agricultural Products for the years 2000–2020.

2.3. Methods

This study assessed the spatial and temporal changes in land use/land cover (LULC) in the study area using land use raster data of 30 m accuracy in conjunction with a land use type conversion matrix, land use dynamics, and LUI techniques. Next, this study used ArcGIS 10.6 to create a 3.5 km × 3.5 km fishing net and calculated the ESV for each land use type and the total ESV of the study area. The ESV was determined using Xie's method [19], in this research, in which the standard equivalence coefficient was adjusted by calculating the economic value produced by food crops per unit area of the study area. Subsequently, the adjusted standard equivalence coefficient was combined with the land use data to obtain the monetarily quantified ESV. The temporal and spatial variations of the ESV were characterized using the Theil index, gradient analysis, and hot spot analysis. Coupled coordination analysis, gradient analysis, and spatial autocorrelation analysis were used to explore the relationship between ESV and LUC. In order to delve further into the relationship between ESV and LUC, a polynomial fit was chosen to reveal the correlation between LUI and CCD (Figure 2).

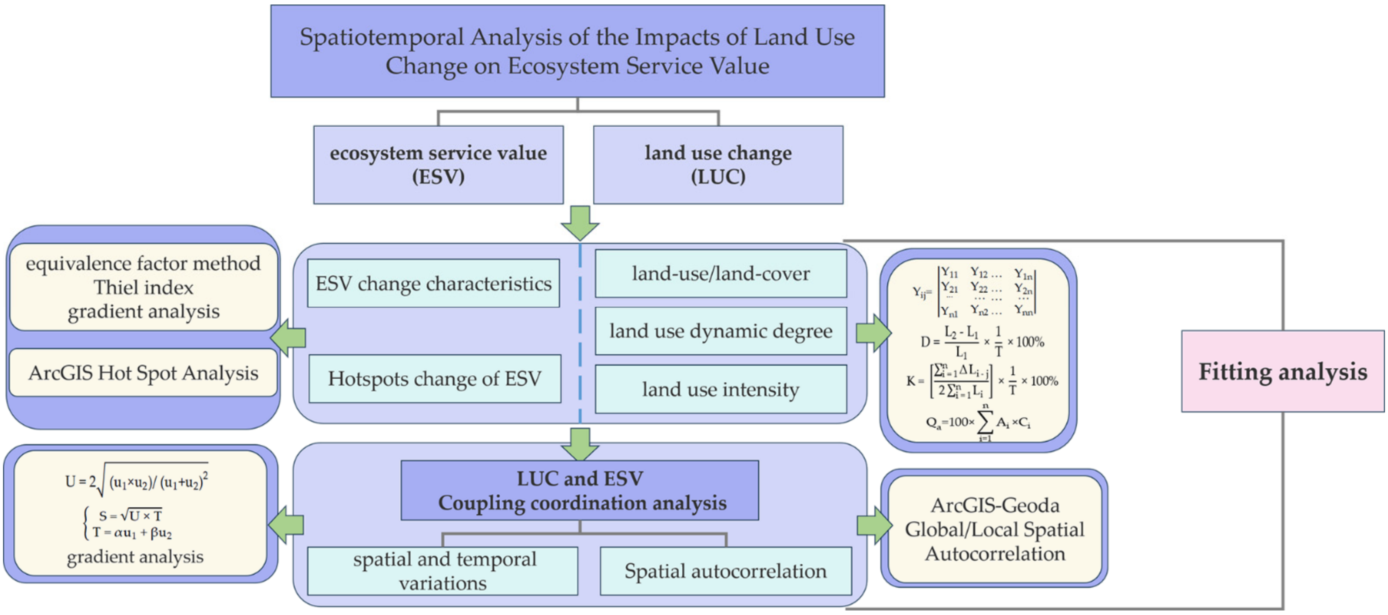

Figure 2. Research framework.

2.3.1. LUC Characteristics

(1) LULC

A land use-type transfer matrix was employed to clarify the land use characteristics and the transfer path between different land use categories:

$$Y_{ij} = \begin{vmatrix} Y_{11} & Y_{12} & \dots & Y_{1n} \\ Y_{21} & Y_{22} & \dots & Y_{2n} \\ \dots & \dots & \dots & \dots \\ Y_{n1} & Y_{n2} & \dots & Y_{nn} \end{vmatrix} \quad (1)$$

where Y is the study area; i denotes the LULC in the initial stage of the study; j corresponds to the LULC in the terminal stage of the study; and n represents the number of land use types.

(2) Land use dynamic degree

Single and integrated dynamic land use models were proposed to better represent the land use coverage and interconversion intensity of each land use type [50]:

$$D = \frac{L_2 - L_1}{L_1} \times \frac{1}{T} \times 100\% \quad (2)$$

where D denotes the degree of single land use dynamics; the area of a specific land use type at the start and completion of the study are indicated by the variables L_1 and L_2, respectively; and T is the period of the study.

Integrated land use dynamics was utilized to characterize the degree of interconversion of each land use type:

$$K = \left[\frac{\sum_{i=1}^{n} \Delta L_{i-j}}{2 \sum_{i=1}^{n} L_i} \right] \times \frac{1}{T} \times 100\% \quad (3)$$

where K represents the degree of integrated land use dynamics; L_i represents land use type i in the initial stage of the study; $\Delta L_{i\text{-}j}$ represents the absolute value of the area of type i land converted into another land type; and T is the period of the study.

(3) LUI

The LUI can be classified into four classes: unutilized land (class 1); water body, forest, and grassland (class 2); agricultural land (class 3); and construction land (class 4) [51,52]:

$$Q_a = 100 \times \sum_{i=1}^{n} A_i \times C_i \quad (4)$$

where Q_a denotes the combined LUI; A_i represents the level of LUI; and C_i corresponds to the proportion of land used for each land use type.

2.3.2. ESV Estimation

(1) Standard equivalent

The ESV equivalence factor can be calculated by taking 1/7 of the market value of the average crop yield in the study area [53]:

$$E_a = \frac{1}{7} \times \sum_{i=1}^{n} \frac{m_i p_i q_i}{M} \quad (5)$$

where E_a corresponds to the economic worth of the production service that a unit of a farming ecosystem may supply; i indicates the kind of crop; p_i represents the national average market price of the i crop; q_i denotes the output of i crop; m_i denotes the acreage of i crop; and M indicates the aggregate area of n crops.

$$ESV_{\mathrm{i}} = A_i \times \sum_{j=1}^{5} V_{ij} \quad (6)$$

$$ESV_n = \sum_{i=1}^{m} ESV_i \quad (7)$$

At every grid point, ESV_i represents the ESV for land use type i; A_i stands for the land use area; m denotes the number of land use types; V_{ij} represents the unit value of ESV category j of land use i; and ESV_n indicates the overall ESV of cell n.

(2) Theil index

The Theil index, known as a common economic index, can be used to illustrate the extent of the disparity between regions and to estimate the size of the inter-regional variations in the ESV [54]:

$$T_a = \sum_i \frac{ESV_i}{ESV} \ln \frac{ESV_i/ESV}{S_i/S} \quad (8)$$

where T_a stands for the inter-area Theil index; S_i represents the area of the i-th region; ESV indicates the overall ESV; and S denotes the entire area. The greater the variation in the ESV between regions, the higher the Theil coefficient.

(3) Gradient analysis

The circle method of gradient analysis enables the effect of circles on the spatial gradient of individual urban elements to be explored [55]. This research used ArcGIS 10.6 to construct buffers to form circles, and the element values were calculated separately for each circle:

$$D_i = \frac{\sum_{j=1}^{n} D_j}{\sum_{j=1}^{n} S_j} \quad (9)$$

where D_i indicates the average elemental value of the i-th circle; S_j denotes the area of cell j contained in the i-th circle; D_j represents the primary count of cell j; and n corresponds to the number of cells in each circle.

2.3.3. Coupled Coordination Relationship between LUI and ESV

The CCD between LUI and ESV was calculated by using the model for coupled coordination [56,57]:

$$U = 2\sqrt{(u_1 \times u_2)/(u_1 + u_2)^2} \quad (10)$$

$$\begin{cases} S = \sqrt{U \times T} \\ T = \alpha u_1 + \beta u_2 \end{cases} \quad (11)$$

where U describes the degree of coupling; U_1 and U_2 are the normalized values of LUI and ESV calculated by using the polar variance method of normalization, respectively; S stands for CCD; and T denotes the index of system comprehensive coordination; α represents the weight of LUI and β indicates the weight of ESV, and they are both set to 0.5 [58].

$$K'_{xi} = \frac{K_{xi} - \min(K_{xi})}{\max(K_{xi}) - \min(K_{xi})} \quad (12)$$

K_{xi} equals the initial value of the *i*-th indicator; K'_{xi} denotes the standardized indicator data.

According to current researches, the CCD can be classified as having a severe imbalance ($0 \leq U < 0.2$), moderate imbalance ($0.2 \leq U < 0.4$), essential coordination ($0.4 \leq U < 0.6$), reasonable coordination ($0.6 \leq U < 0.8$), and high coordination ($0.8 \leq U \leq 1$) [59].

2.3.4. The Polynomial Fit of the LUI to the CCD

This study explored how the degree of coupled coordination between LUI and ESV fluctuates with LUI by simulating the variation curves between LUI and CCD with the polynomial fit feature in Origin 2021 software. This study chose the second-order polynomial in this software, and the normalized LUI and CCD were the independent and dependent variables, respectively. The curve represented the coupling degree trends of the LUI and ESV as the LUI changed.

3. Results

3.1. The LUC of Guiyang

In Guiyang, construction land accounted for the majority of LULC between 2000 and 2020. Construction land generally increased as farmland, forest, grassland, and unused land diminished. The most significant changes occurred in the construction land and water body, which increased by 146.752% and 49.752%, respectively. Forest exhibited the least rate of change, dropping by 0.762% in 2020 compared to 2000. Throughout these 20 years, farmland, forest, and grassland were the three main land categories, accounting for the most significant percentage of the whole area (Figure 3). The regions where construction land expanded between 2000 and 2020 focused on Wudang, Baiyun, Guanshanhu, Xifeng, and Qingzhen; the most considerable percentage growth was in Guanshanhu, and the smallest was in Yunyan. The highest growth rate of farmland was in Xifeng (0.978%). Guanshanhu had the highest decline in farmland, at 44.529%. The forest areas in Baiyun showed the most excellent rate of improvement at 10.427%, and Nanming had the worst at −15.134%. The percentage increase in grassland areas was negative in all counties, with the lowest in Yunyan at −70.880%. Kaiyang underwent the most rapid expansion in the water area, at 1047.036%. Only Guanshanhu and Qingzhen had unused land by 2015; by 2020, only Qingzhen had unused land.

In 2000–2020, the most significant amount of land transferred in was construction land (377.0101 km^2), whereas the largest amount of land transferred out was farmland (418.775 km^2). The majority of forest had been turned into farmland, the majority of unused land into construction land, and the majority of grassland, water body, and construction land into forest. The conversion of the most incredible amount of grassland into farmland occurred between 2000 and 2005; the most incredible amount of grassland to forest conversion happened between 2005 and 2010; the greatest amount of farmland was converted into forest between 2010 and 2015; and the largest conversion of farmland into construction land occurred between 2015 and 2020 (Figure 4).

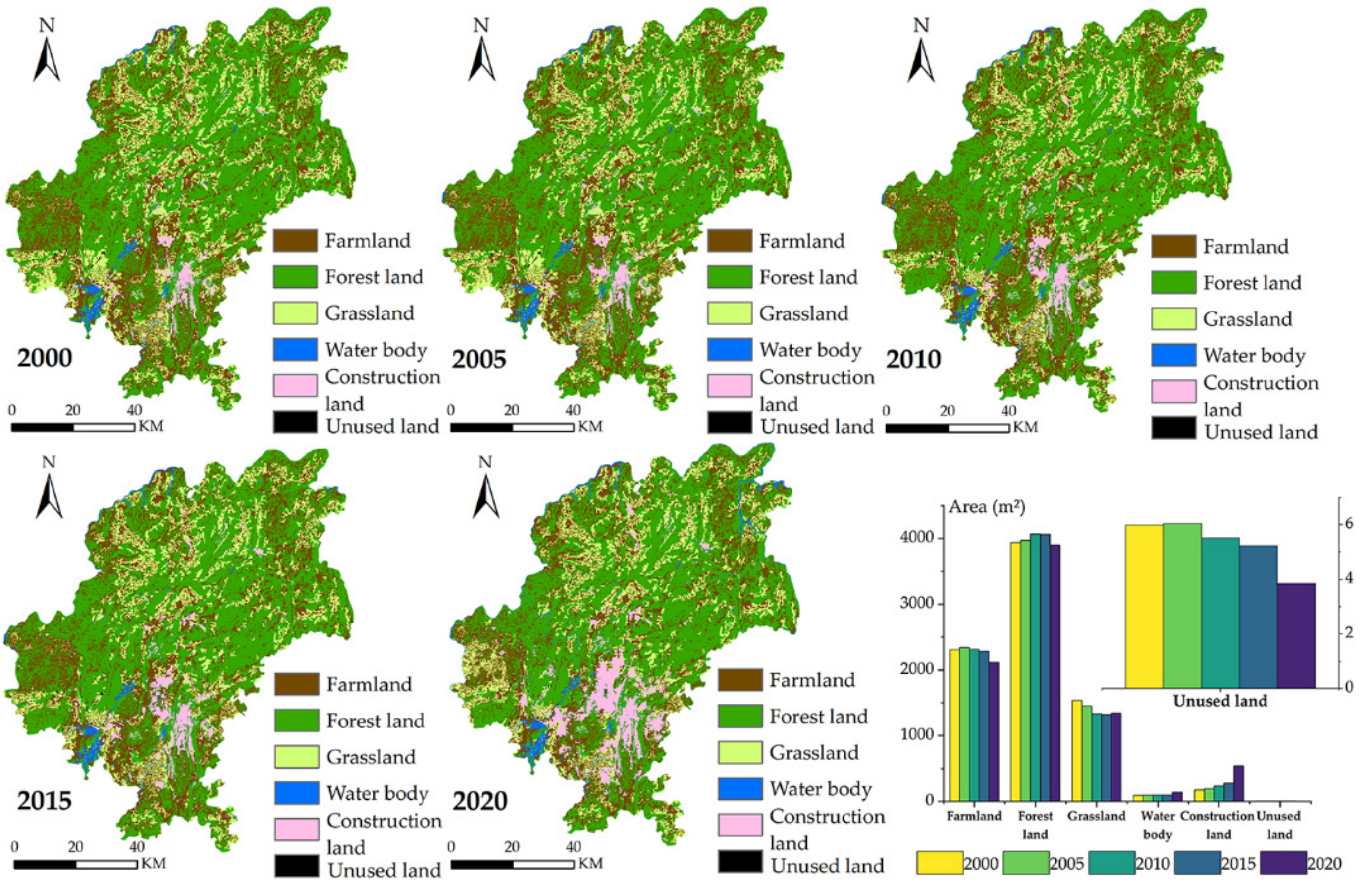

Figure 3. The characters of LULC in Guiyang.

Between 2000 and 2020, the integrated land use dynamic degree was 0.258%. Assessments of the alterations in land use have been conducted throughout time every five years. The percentage of integrated dynamics degree was 0.205%, 0.359%, 0.110%, and 0.816% in the years 2000–2005, 2005–2010, 2010–2015, and 2015–2020, respectively. The integrated dynamics of the various land use types exhibited a pattern that first increased, then decreased, then increased once again, and peaked at the fourth stage, according to the data. For each land use type, the single land use dynamic degree outcomes from high to low were in the following order: construction land > water body > forest > farmland > grassland > unused land (Figure 5). For both the construction land and the water body, the dynamic degree was 2.621% and 10.527%, respectively, and overall, only these two land types had positive dynamics from 2000 to 2020: −0.410% and −0.619% for the dynamics of farmland and grassland, respectively. Following the increase in farmland dynamics in 2000–2005, the 2005–2015 dynamics remained negative. The grassland dynamics were negative in 2000–2015; the 2015–2020 dynamics increased to 0.310%. Forest dynamics increased from 2000 to 2010 and continued to decline from 2010 to 2020. The unused land dynamics were only positive in 2000–2005; they were negative in 2005–2020 and substantially decreased in 2015–2020. In the period 2000–2020, LUI displayed a consistent increasing tendency. The LUI of Guiyang maintained an upward trend, with the largest increase, at 13.852%, in Yunyan. The LUI of Xiuwen, Xifeng, Kaiyang, and Wudang was at a lower level. The LUI of Baiyun, Guanshanhu, Huaxi, and Qingzhen was at a moderate level (Figure 5).

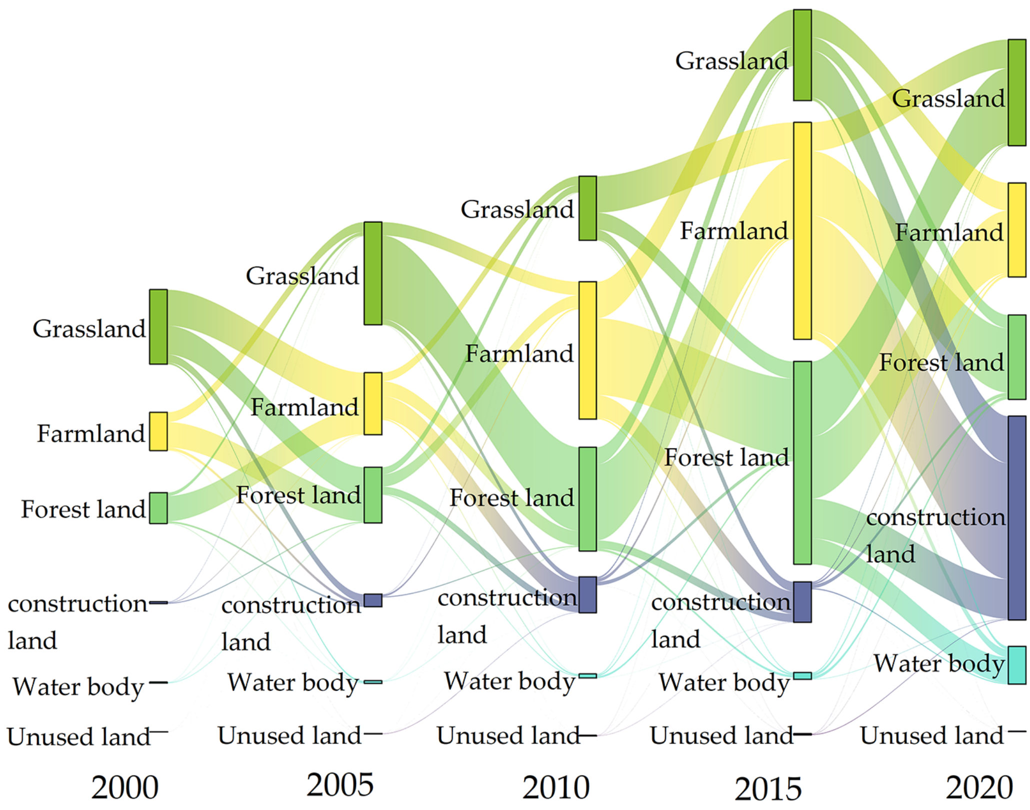

Figure 4. The changes in LULC in Guiyang.

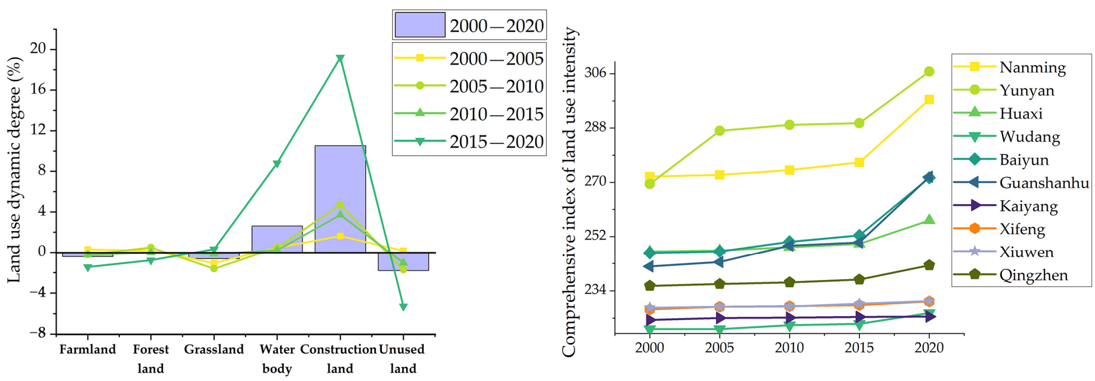

Figure 5. Single land use dynamic degree and comprehensive index of LUI.

3.2. Features of ESV Change

From 2000 to 2020, the ESV trended lower before rising again. From 2000 to 2015, it was declining, but the rate of decline slowed down over time (Figure 6a–e). The ESV over five periods was 2130.018, 2119.914, 2114.006, 2108.909, and 2149.387 million dollars, with a slight overall change of 0.909%. The northeast of Kaiyang, north of Xifeng, and south of Qingzhen were the primary locations with high ESVs; the low-ESV areas were mainly in Yunyan, Nanming, Baiyun, Guanshanhu, Huaxi, the west of Qingzhen, Xiuwen, the northwest of Xifeng, and the central part of Kaiyang. The Theil index was observed to increase, which indicates a gradual widening of the gap in ESV within the region. The reason for the increased inequality in ESV within regions could be the irrational development and utilization of land by humans, and the LULC study found that the gradual increase in land for construction came at the expense of the decrease in ecological lands, such as forest and grassland. The degree of economic development varied between regions, as did the degree of land exploitation and use. Figure 6a–e demonstrates that the ESV was usually lower in regions close to urban centers; the imbalance in inter-regional development affected the overall variability of the ESV in Guiyang city. The six main urban areas of Guiyang showed a downward tendency in ESV from 2000 to 2020, with the highest rate of decrease recorded in Yunyan, which reached −28.088%. Among the "one city and three counties", Kaiyang showed the most significant change, rising by 10.825% in the period 2015–2020; the value for Xifeng began to rise between 2015 and 2020, with growth rates of 0.411% and 0.127%, respectively. Between 2015 and 2020, there were increases of 2.095% in Qingzhen and 2.002% in Xiuwen. The water body experienced the most enormous growth in ESV, whereas the unused land saw the most significant decline. From 2000 to 2005, only grassland showed a decrease in ESV, which persisted until 2015. Farmland and unused land had a declining ESV starting in 2005 and continued to do so until 2020. The year 2010 was the starting point for the fall in forest land ESV. The ESV for water body grew between 2000 and 2020 (Table 1).

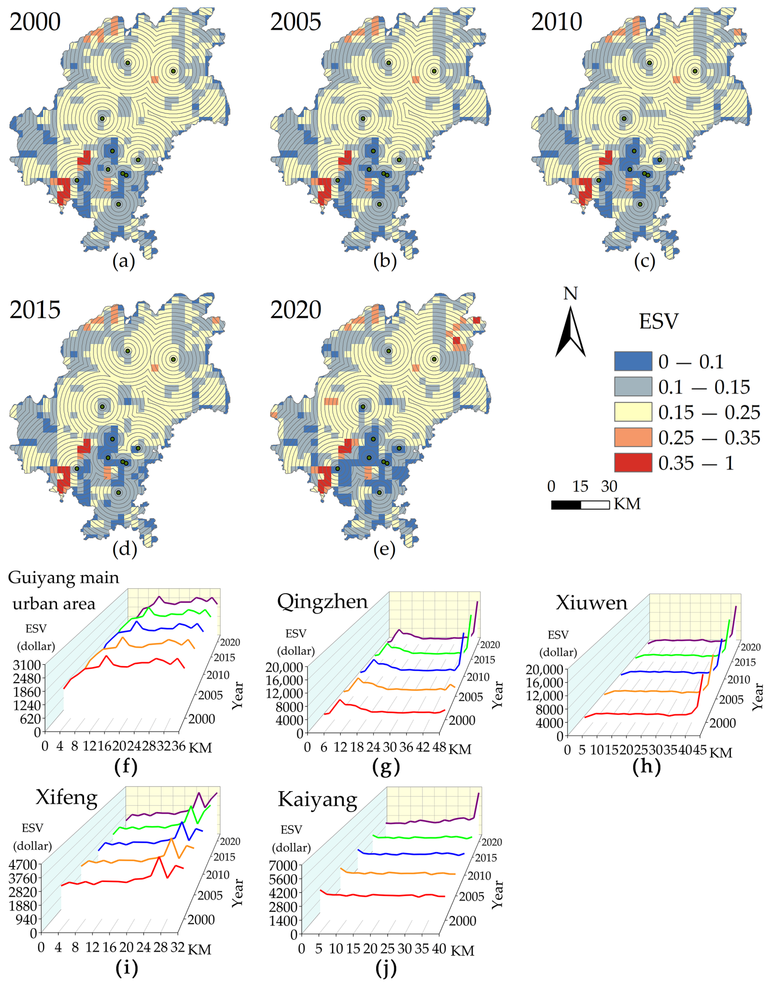

Figure 6. Gradient analysis of ESV changes in Guiyang.

Table 1. ESV and Theil index changes from 2000 to 2020 in Guiyang.

	Year	Farmland	Forest Land	Grassland	Water Body	Unused Land	Total
ESV (millions of dollars)	2000	166.964	1237.918	518.916	206.197	0.022	2130.018
	2005	169.306	1248.513	491.014	211.058	0.022	2119.914
	2010	167.364	1279.280	451.367	215.975	0.020	2114.006
	2015	165.337	1277.606	447.739	218.209	0.019	2108.909
	2020	153.285	1227.120	454.681	314.287	0.014	2149.387

Table 1. *Cont.*

	Year	Farmland	Forest Land	Grassland	Water Body	Unused Land	Total
Change rate (%)	2000–2005	1.403	0.856	−5.377	2.357	0.843	−0.474
	2005–2010	−1.147	2.464	−8.075	2.330	−8.596	−0.279
	2010–2015	−1.211	−0.131	−0.804	1.034	−5.241	−0.241
	2015–2020	−7.289	−3.952	1.550	44.030	−26.413	1.919
	2000–2020	−8.193	−0.872	−12.379	52.420	−35.726	0.909
Year		2000	2005	2010	2015	2020	
Theil index		0.0046	0.0052	0.0053	0.0056	0.0100	

The main six urban areas of Guiyang were considered as a whole, while Qingzhen, Xiuwen, Kaiyang, and Xifeng were viewed as a whole. Their commercial centers have been selected to draw buffer zones with an interval of 2 km (Figure 6f–j). Overall, the value trend in each area changing with the circle remained the same from 2000 to 2020. The main urban areas of Guiyang within the 2–10-km circles were considerably less valuable in 2020 than in 2000–2015 (Figure 6f). Kaiyang showed much-improved values after the 16-km circle compared to previous years, with the highest rise occurring inside the 40-km circle (Figure 6j). The 2-km circle values of Xifeng were considerably lower from 2010 onwards than in 2000–2010, and after the 28-km circle, they remained high in 2015–2020 before starting to fall in value inside the 30-km circle in 2010 (Figure 6i). The trend for Xiuwen in 2000–2020 was unchanged, and the values inside the 40-km circle in 2015 and 2020 were markedly higher than in the other years (Figure 6h). Qingzhen showed an upward trend in the 46–48-km circles in 2000, but the value in the 48-km circle fell again in 2005 and then rose sharply after 2010 until the beginning of the 46-km circle, growing each year (Figure 6g).

The south of Qingzhen, Guanshanhu, the north of Xiuwen, the north of Xifeng, and the east and west of Kaiyang were the primary locations of hot-spot changes in ESV in Guiyang. The cold-spot changes were primarily located around Yunyan, Nanming, and the south of Baiyun, as well as the Huaxi, Qingzhen, Xifeng, and Kaiyang border areas (Figure 7).

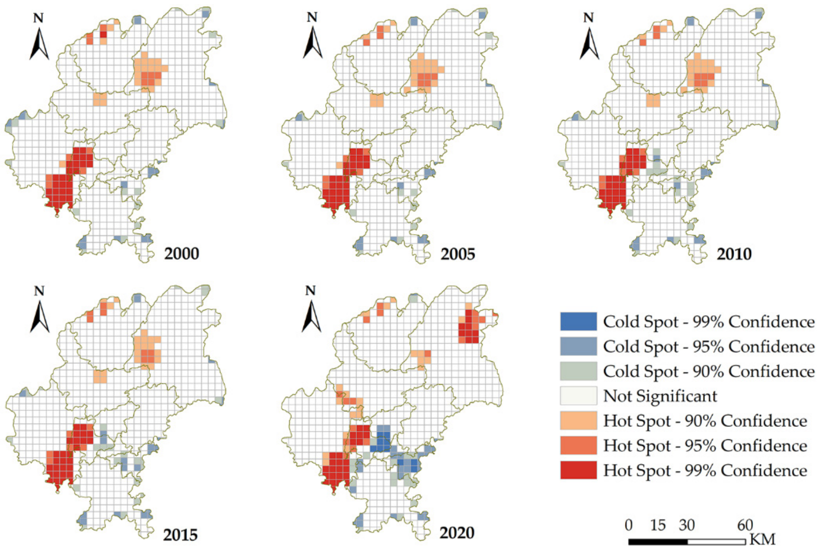

Figure 7. Hot spots for change in the ESV in Guiyang from 2000 to 2020.

3.3. *Evaluation of LUC and ESV Coupling Coordination*

The 2000–2020 LUI and ESV coupling coordination in Guiyang was mainly primary coordination and endangered dysfunction (Figure 8a–e). Primary coordination accounted for most of the coupling coordination in 2000 (Figure 8a), accounting for 21.989% of it, but was overtaken by endangered dysfunction in 2015 (Figure 8d), with endangered dysfunction reaching 21.020%. Severe dislocation and primary coordination regions gradually shifted to endangered dislocation. The areas of severe dislocation rose by 16.129% from 2005 to 2010 and progressively decreased from 2010 to 2020. The primary coordination areas shrank by 24.205% between 2000 and 2020. A growth of 29.206% in endangered dislocation regions occurred between 2000 and 2020, and the most dramatic change occurred between 2015 and 2020. Both intermediate coordination and severe dislocation were centered in Qingzhen city, but the proportion was tiny. The overall level of coupled coordination in Guiyang did not change much between 2000 and 2020, and neither did the tendencies within the districts. Qingzhen (Figure 8g), Xiuwen (Figure 8h), Kaiyang (Figure 8j), Xifeng (Figure 8i), and the main six urban areas of Guiyang (Figure 8f) were considered individual areas. Their economic hubs have been chosen to provide buffer zones spaced 2 km apart. The level of coupled coordination between the main urban areas of Guiyang and Qingzhen was characterized by a high level of coupled coordination in the areas surrounding the regional centers. Owing to their high degrees of urbanization and building, Qingzhen and the main metropolitan regions of Guiyang showed a high degree of interaction between LUI and ESV. Every Xiuwen circle had a CCD marked low in the center and high on both sides. Specifically, before the 8-km circle, the CCD of Xiuwen dropped with the distance from the regional center. Then, it fluctuated at a low level until a noticeable upswing occurred at the 32- and 42-km circles. Up to the 30-km circle, the CCD in Xifeng was very flat; nevertheless, the 30–32-km circle showed a definite downward trend. Kaiyang displayed a comparable pattern, with little change until the 28-km circle and a continuous decline in CCD levels after a brief rise in the 28–32-km circle.

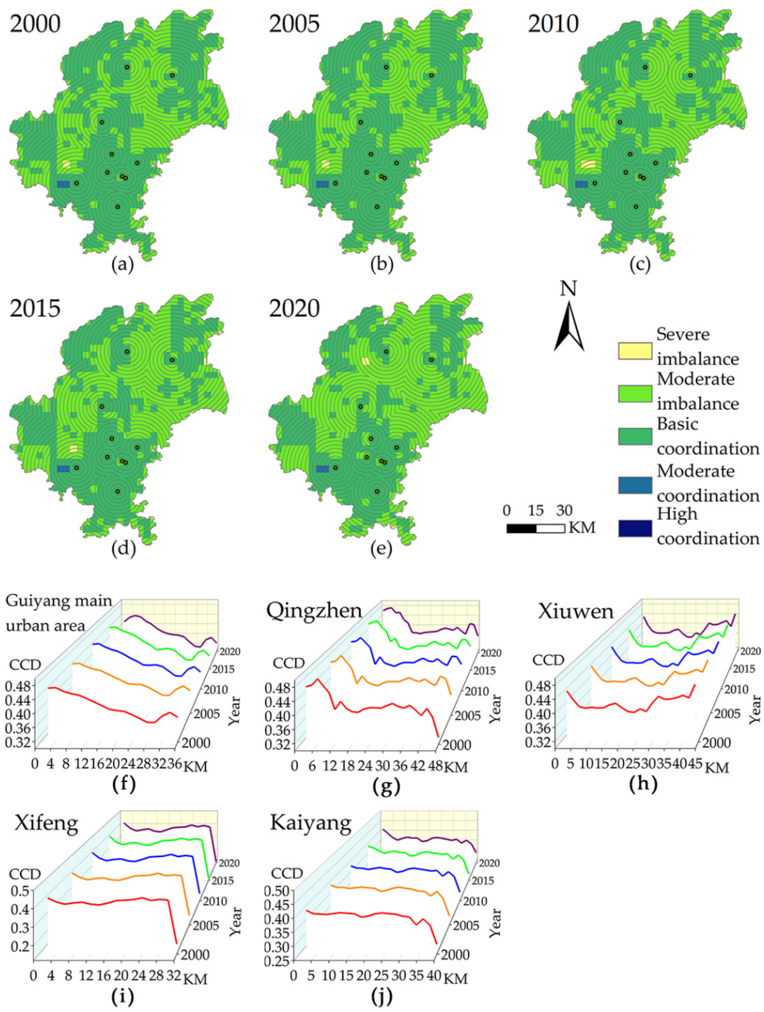

Figure 8. Gradient analysis of CCD changes in Guiyang.

A global autocorrelation analysis of CCD indices for LUI and ESV in Guiyang was conducted using ArcGIS10.6 software. For each of the five time periods from 2000 to 2020, the global Moran's I value of the Guiyang CCD was > 0.26 with $p < 1$. Significant regional variances and a somewhat positive spatial correlation were observed in the degree of coupling coordination, with a maximum value of 0.282 in 2015 and a minimum value of 0.261 in 2020. Low–low and high–high aggregation types were found to be the primary characteristics of Guiyang, according to the results of the localized spatial autocorrelation. Huaxi, Yunyan, Nanming, Guanshanhu, Baiyun, southern Wudang, southern and northern Qingzhen, the northeastern edge of Xifeng, and the central part of Kaiyang were the prominent locations of high–high aggregation; east Qingzhen, northeastern Wudang, and the western and eastern borders of Kaiyang were all areas of low-low aggregation (Figure 9).

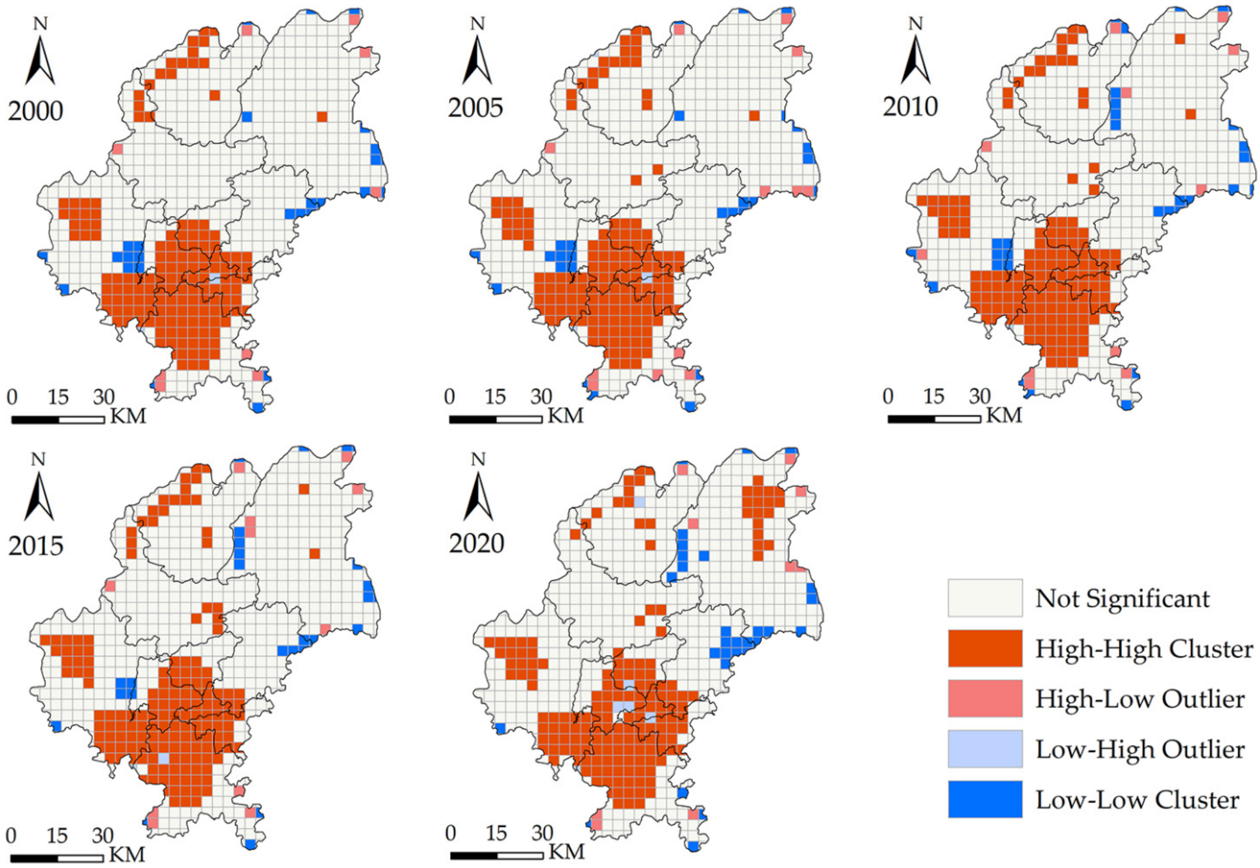

Figure 9. Local indicators of the spatial association of CCD in Guiyang from 2000 to 2020.

3.4. Polynomial Fitting Analyses of the LUI and CCD

The polynomial-fitted R^2 values were all >0.6, and the p-value was <0.000, suggesting that the equation has some explanatory effect on the change process in LUI and its coupling coordination with ESV (Table 2). Specifically, an inflection point appeared in all five periods of the fitting curve from 2000 to 2020, and the peak values of the CCD index appeared when the LUI index was 0.5, 0.497, 0.526, 0.496, and 0.499, respectively, beginning to change from an upward trend to a downward trend. The fitted curve (Figure 10) had an inverted U-shape, where the level of coupling between LUI and ESV peaked and then declined as LUI grew. This reveals that from the onset of LUI growth, the relationship between LUI and ESV progressively became stronger. However, as LUI continued to increase, the coupling index progressively declined following its highest value, which suggests that at this point, the interaction between LUI and ESV was less intense.

Table 2. Expression and inflection points between LUI and CCD.

		2000	2005	2010	2015	2020
		Expression: y = Intercept + B1 × x + B2 × x^2				
R^2		0.619	0.643	0.706	0.675	0.825
P		0.000	0.000	0.000	0.000	0.000
Intercept		0.25953 ± 0.00449	0.26097 ± 0.00437	0.26385 ± 0.00364	0.25066 ± 0.00397	0.26452 ± 0.00233
B1		0.90071 ± 0.03268	0.90544 ± 0.03124	0.87213 ± 0.02591	0.95957 ± 0.0292	0.87428 ± 0.01744
B2		−0.90321 ± 0.05142	−0.90964 ± 0.04779	−0.82857 ± 0.03721	−0.96629 ± 0.04218	−0.87525 ± 0.02233
Inflection	LUI	0.500	0.497	0.526	0.496	0.499
	CCD	0.483	0.486	0.493	0.489	0.484

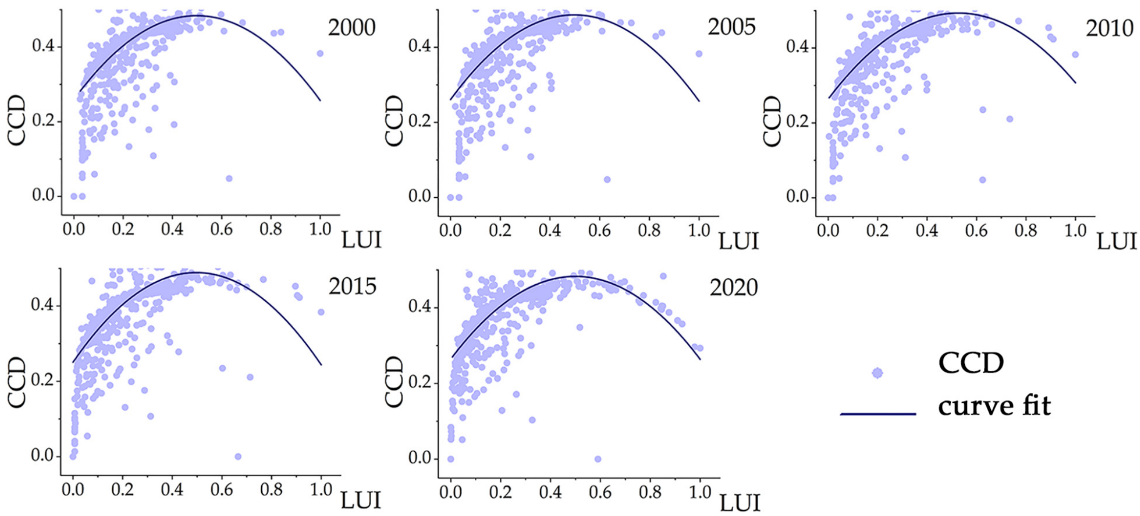

Figure 10. Fitting relationships between LUI and CCD from 2000 to 2020.

4. Discussion

4.1. Dynamics of Land Use, ESV, and Their Coupling Relationship in Guiyang

The patterns of urban ecosystems have been dramatically impacted by modifications to the urban land use structure brought about by the current imperative for fast urban expansion [60]. This analysis shows that between 2000 and 2020, the amount of land used for construction and the growth of water body in Guiyang dominated the variation in land use, while the amount of farmland, forest land, grassland, and unused land generally reduced. Farmland, forest, and grassland were the primary input categories used for expanding construction land. Farmland and forest land were the main drivers of the growth of the water body category. The growth of construction land in Guiyang resulted in the loss of farmland, forest land, and grassland, which reduced the ESV from 2130.018 to 2108.909 million dollars, or 0.991%, between 2000 and 2015. However, because of the growth of the watershed from 2015 to 2020, the ESV increased by 1.919% to 2149.387 million dollars. The loss of agriculture, forest, and grassland along with urbanization were all contributing factors to the overall drop in ESV; nevertheless, the preservation and restoration of water body drove an increase in the ESV. This finding was consistent with previous studies conducted in Southwest China and indicated that the extension of the water body area was the primary cause of the increase in ESV [61]. The water body area in the Yunnan–Guizhou Plateau expanded between 2001 and 2020 [62]. Between 2000 and 2020, Guizhou Province did not experience a notable uptick in precipitation; the development of water conservation projects was the primary cause of the increase in water area [63]. The Qianzhong Water Conservancy Hub project has effectively increased the amount of surface water storage in Guiyang. Compared with other land use types, the water body category had a more significant coefficient of value per unit area; therefore, even though water body was not very large overall, it substantially influenced changes in the ESV.

The LUI can have a direct or indirect impact on biodiversity. Increases in LUI may result in biodiversity loss, land degradation, higher carbon emissions, and other environmental effects [64–66]. The urban center areas of Guiyang, Yunyan, and Nanming had a much higher LUI than other places because of the density of their construction land and a small area of ecological land. Xifeng, Xiuwen, Kaiyang, and Wudang had less LUI and ecological space as they were less urbanized overall. As a mountainous city, geographic factors and government policies influenced and restricted urban expansion and LUC in Guiyang [67]. In Guiyang, since 2000, economic development has been increasing, and its ESV was low in the central city. The regions of Kaiyang, Qingzhen, Xifeng, Xiuwen, Huaxi, and Wudang have been included in most high ESV areas. These regions produced more ESV because they had a lower proportion of construction land and were more prosperous in ecological resources than Guanshanhu, Baiyun, Yunyan, and Nanming. The ESV of the Guiyang districts showed different fluctuations with distance from the regional center, and the fluctuation trends did not change much over time, which indicated stability in the interregional LUC. The ESV was often lower near the regional center, showing a negative impact of urbanization on the ecosystem. The ESV was greater and even exhibited a considerable increase in the regions far from the regional center, which suggested that these locations had superior ecological environments. Overall, LUI and ESV climbed by 2.93% and 0.909%, respectively, between 2000 and 2020, with primary harmonization and endangered dislocation accounting for most of their CCD-level types. Unreasonable land usage was one major factor that contributed to the low level of coupled coordination between LUI and ESV. One can determine how benign their interaction was by examining the CCD between LUI and ESV. It is essential to actively develop the economy while concentrating on preserving and rehabilitating the natural environment.

4.2. Polynomial-Fitted Relationship between LUI and CCD

It was evident from the inverted U-shaped curve of the Guiyang LUI and LUI–ESV CCD that the two phases of their relationship could be separated. During the initial phase, the degree of coupling coordination rose in tandem with the LUI. Land use still negatively affected the permitted range of ecosystems, and the LUI was not surprising. The close interaction between land use and ecosystem services persisted, and there was still potential to enhance the degree of coordination between the two. The second stage could be conceptualized as a large-scale extension of urbanization, and it was characterized by a rise in construction land, a corresponding increase in the pace of urbanization, an invasion of ecological space, and the degradation of the natural environment. The CCD between ecosystems and land use declined as a result of all these issues. At this point, the amount of LUI–ESV coupling coordination peaked and then began to display a declining trend as the LUI reached a particular level and continued to grow. When the LUI reached a high level, the LUI–ESV coupling coordination reduced in degree. This could be explained by the fact that the LUI gradually grew with the development of urbanization and that the harm produced by humans to the ecological environment affected the services and functions of the ecosystem, which resulted in a continual drop in the degree of LUI–ESV coupling coordination.

In summary, the polynomial-fitted relationship established the mutual influence, dependency, and limitations between land use and LUI–ESV CCD. Accordingly, the government should implement ecological protection measures at various stages of urbanization to prevent the negative effects of irrational land use on ecosystems. Future planning of Guiyang for ecological environments and urban development needs to consider the evolutionary trend in this relation. Plans for the development of urban areas should create ecological networks and delineate the limits of ecological control zones. Encouraging communities to conserve and restore natural resources through appropriate financial incentives is one way to support the preservation of existing ecosystems.

4.3. Limitations and Future Research

The way that humans interact with the environment produces a pattern of land use, which is essential for ecosystem services [68]. Ecosystem sustainability and the advancement of human society are closely linked. This study estimated the ESV of Guiyang from 2000 to 2020 using the equivalence coefficient approach as a means for quantifying the benefits produced by the ecosystem. However, data accuracy, such as land use and food production, affected the value of the monetized ESV. In future studies, the characteristics of karst regions should be considered, and the relevant literature should be referred to construct a revised model in order to provide a more accurate estimate of the ESV [69,70]. In addition, this study explored the relationship between land use and ESV, but it has not yet analyzed the driving factors that affect the relationship between land use and ESV. Techniques such as Bayesian spatiotemporal hierarchy models [71], econometric models [72], and geographic probes [73] can be utilized to gain additional insights into the variables that affect ecosystem services and land use. Meanwhile, the characterization of karst ecosystem services will be further considered in future studies.

5. Conclusions

This study analyzed the LUC and ESV in Guiyang from 2000 to 2020 from both temporal and spatial viewpoints with the 30 m × 30 m land use raster data and the fishing net of 3.5 km × 3.5 km. The CCD model was used to quantify the benign CCD and the synergistic connection between LUI and ESV. The findings in this study demonstrated that the main cause of changes in the land use categories in Guiyang was the growth of the water body and construction land categories, with farmland, grassland, and forest making up the bulk of the categories of land output. The larger watershed was the main factor that drove the increase in the Guiyang ESV, which first trended downward before reversing and trending upward. The coupling coordination level of LUI and ESV was mainly dominated by primary coordination and near-dissonance, which indicated that the two were primarily constrained by each other at a low level. The fitting examination of the coupling coordination levels of LUI and LUI–ESV revealed an inverted, U-shaped curve relationship with a polynomial fit. Throughout the early growth stage of LUI, there was a rising trend in both the degree of benign coupling and the interaction between land use and ecosystems. The land use-disturbed ecosystem functioned, to some extent, as a result of the ongoing increase in LUI, which lowered the degree of benign coupling between the two. The importance of water body for ESV growth cannot be ignored during urbanization, and there is a need to focus on the protection of water body during future urbanization. According to the level of urbanization and development and considering the needs of social development and ecological sustainability, the relevant departments should formulate appropriate development plans. Governments must promptly control human interference with ecosystem services until land use intensity has caused severe damage to ecosystem services. The results of this study were crucial to understanding how ecosystem services and land use are related, as well as how these services change as a result of urbanization. This study offers a theoretical foundation for the administration and design of ecosystems during a subsequent urbanization phase.

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