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A Multi-Scenario Simulation and Dynamic Assessment of the Ecosystem Service Values in Key Ecological Functional Areas: A Case Study of the Sichuan Province, China

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Abstract: The ecosystem service value (ESV) is an important basis for measuring an ecological environment's quality and the efficient management of ecosystems. It is particularly necessary to explore a proven methodology for assessing and predicting ESV dynamics coupled with policy-oriented scenarios that can provide a theoretical groundwork for macro decision, particularly in the context of implementing ecological protection and restoration projects. This study selected the land cover (LC) of Sichuan Province at five periods and the spatiotemporal dynamic equivalent factor method to assess the ESVs from 2000 to 2020. Additionally, the study coupled the Markov chain and GeoSOS-FLUS model, and predicted the future pattern of ESVs under four future development scenarios. The results show that (a) the areas of forests, shrubs, waters, wastelands, wetlands, and impervious areas showed a continuous increase from 2000 to 2020, with the most frequent interchanges occurring among croplands, forests, and grasslands. (b) The implementation of ecological protection and restoration projects led to a 13,083.32 $\times 10^8$ yuan increase in ESV, and barycenter of the ESVs is located in the northeastern part of Ya'an and exhibits a tendency to move towards the northeast. (c) The ESV aggregation pattern of each city has remained unchanged, with Ganzi being the only city with a high aggregation. Overall, there are more conflict cities than coordination cities between economic development and the ecological environment. (d) The total ESV in 2025 will continue to increase under all development scenarios, reaching a maximum of 50,903.37 $\times 10^8$ yuan under the EP scenario. This study can provide insights for ecological planning decisions and sustainable regional socio-economic development.

Keywords: ecosystem service value; ecological protection and restoration projects; GeoSOS–FLUS; spatiotemporal characteristics

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1. Introduction

The ecosystem, consisting of organisms and the environment, plays a crucial role in supporting and advancing human civilization [1]. Consequently, research on ecosystems has gained significant attention in fields such as ecology and geography. Ecosystem services (ESs) encompass the various benefits that humans receive from ecosystems, including those of hydrological management, climate regulation, soil preservation, and other supporting services [2–4]. These services not only provide essential resources for human survival but also ensure the continuity of natural environments and human welfare [5,6]. ESs can be quantified in monetary terms, known as the ecological service value (ESV) [7,8]. This involves analyzing basic data, ecology, and economics to assess potential socio-economic development through its monetary value [9].

The assessment of ESV is the basis for implementing ecological protection measures, conducting environmental and economic accounting, and formulating ecological compensation policies [10]. There are two primary approaches for evaluating and predicting an ESV: the method of unit service function pricing and the method of the unit area value equivalent factor [11]. The former method involves simulating the ecosystem service functions of particular regions through the establishment of a production equation [12,13]. However, this method for evaluating ecosystem service formation has limited explanatory power due to its complex calculation processes and numerous input parameters [14,15]. In contrast, the equivalent factor method offers a more concise and intuitive approach. This method differentiates diverse categories of ecosystem service functions and establishes measurable benchmarks to create the value equivalents of distinct service functions by considering the geographical extent of the ecosystem. Currently, the most used method is that of the unit area value equivalent factor. For example, Costanza et al. [16] established the global ESV equivalent factor table in 1997, laying a theoretical foundation for relevant research. Xie et al. [11] formulated and refined an equivalent table of the ESV per unit area for China's terrestrial ecosystem. Duan et al. [17] assessed the value of the ecosystem services in the Sanjiangyuan region of the Tibetan Plateau from 2000 to 2020. Huang et al. [18] analyzed of the spatial and temporal coupling of the human footprint and the ESV in the highly urbanized Pearl River Delta urban agglomeration in China. Numerous scholars have widely utilized this method to investigate the connection between land cover (LC) and ESVs [7,19]. However, some ESV evaluation processes through the equivalent factor method miss the consideration of the changes in the standard unit equivalent factor values because of factors such as currency appreciation, regional development imbalance, and the spatiotemporal heterogeneity of ecosystems and their services [20]. Therefore, it is important to construct a dynamic assessment system to accurately assess and predict an ESV to support decision management for ecological sustainability.

On the other hand, the contradiction between the ecological environment and economic development holds paramount importance within the framework of rapid urbanization [21]. Alterations in LC have a broad impact on ecosystem structures, processes, and functions, thereby significantly affecting ESVs [7,19]. The extensive conversion of cropland, forest land, grassland, and wetland into impervious land has led to severe consequences, including the complete loss of the corresponding ecosystem functions [22,23]. Undoubtedly, LC change is the primary driver behind alterations in the ESV. Therefore, it is imperative that we monitor the process of the ESV change based on LC change to promote the rational protection of natural resources. Additionally, while there has been significant research on ESVs, limited attention has been given to predicting their future trends, which has hampered the pluralistic application of ESV assessments in ecosystem management.

To address these issues, researchers can employ spatial scenario modeling to predict future land cover, which, in turn, allows for the prediction of future ecosystem service values [24]. Several models have been developed and utilized for modeling and predicting future LC, including cellular automata (CA) [25], CA-Markov models [26], artificial neural networks (ANN) [27], and the conversion of land use and its effects at small regional extents (CLUE-Ss) models [28]. Notably, Liu et al. [29] integrated the strengths of both "top-down" and "bottom-up" approaches to develop a geographic simulation and optimization system–future land use simulation (GeoSOS-FLUS) model, which was coupled with the Markov chain model and demonstrated unique functional advantages over other models. At the same time, the model has been recognized as the only LC simulation modelincluded in the International Encyclopedia of Human Geography. Although there have been significant improvements in its flexibility and simulation mechanisms, there is still potential for its further utilization in future ESV projections.

China has recently made significant efforts toward the construction of ecological civilization to facilitate coherence between ecological development and economic progress, while also fostering a harmonious cohabitation of mankind and the environment [30,31]. In addition to enhancing ecological protection, China has also made continuous efforts toward ecological restoration and has actively pursued key ecological protections and restorations such as soil and water conservation, large-scale land greening, and biodiversity protection [32–34]. Several projects, including the Three-North Shelterbelt Program System Construction Project, and the Yangtze River Basin Shelterbelt System Construction Project, have shown significant achievements [35–37]. The assessment results of the ESV serve as a crucial measure for measuring the effectiveness of ecological civilization construction. They enable a better understanding of ecosystem importance, guide various sectors of society to prioritize ecological environmental protection, and provide a scientific basis for decision-making in promoting ecological civilization construction [38]. Sichuan Province acts as a significant ecological barrier in the upper reaches of the Yangtze River and as a vital economic hub in Western China [39]. Sichuan Province has experienced rapid urbanization following the last century, and its urbanization rate has surpassed the national average. This, coupled with its high susceptibility to natural disasters due to its considerable terrain variations and increasing population density, has further exacerbated the disturbance of local ecosystems [40]. Since 2000, Sichuan Province has implemented multiple significant ecological protection and restoration projects, including the restoration of cropland to forests, the protection of natural forest resources, the construction of the shelterbelt system, and the restoration of grazing land to grassland [35]. In this context, there is currently a lack of quantitative support for understanding the characteristics of ESV changes, assessing ecological benefits, and predicting future ESVs [41,42].

In summary, it is particularly necessary that we explore a proven methodology for assessing and predicting ESV dynamics coupled with policy-oriented scenarios that can provide a theoretical groundwork for macro decision, particularly in the context of implementing ecological protection and restoration projects. As the year 2025 marks the conclusion of China's 14th Five-Year Plan and a crucial milestone in achieving the goal of building an ecological civilization, it holds significant importance. Based on the above background, it is particularly necessary that we accurately assess and predict the spatiotemporal patterns of LC and ESV in Sichuan Province, and clarify the characteristics of their changes. Therefore, this study proposes the subsequent research objectives: (1) Explore the spatiotemporal patterns of LC and ESVs in Sichuan Province from 2000 to 2020, considering the implementation of ecological protection and restoration projects; (2) analyze the characteristics and problems of ESV during different time periods, aiming to provide quantitative support for sustainable development decisions; (3) predict the spatiotemporal dynamics of the LC and ESV in 2025 under multiple development scenarios using the GeoSOS-FLUS models.

2. Study Area

Sichuan Province is located in the inland of Southwest China, divided into 21 cities (Figure 1), and spans the first and second steps of mainland China's terrain [43]. Regarding its natural environment, the local climate is mainly subtropical, humid and semi-humid, and 96.6% of the water system in the region flows into the Yangtze River [44]. In addition, the local area boasts remarkable biodiversity, with 145 species of wild animals under key protection [45]. The forest stock volume stands at an impressive 1.897 billion cubic meters, contributing to a forest coverage rate of 39.6% [45]. The grassland in Sichuan Province showcases an exceptional comprehensive vegetation coverage rate of 85.6%. It is the ecological barrier in the upper reaches of the Yangtze River and the Yellow River and a rich repository of diverse biological resources [46]. However, the terrain in Sichuan Province exhibits notable variations, and the economic development within its urban areas is characterized by disparities. Urban resident populations are steadily expanding, leading to an escalating consumption of and heightened demands for natural resources.

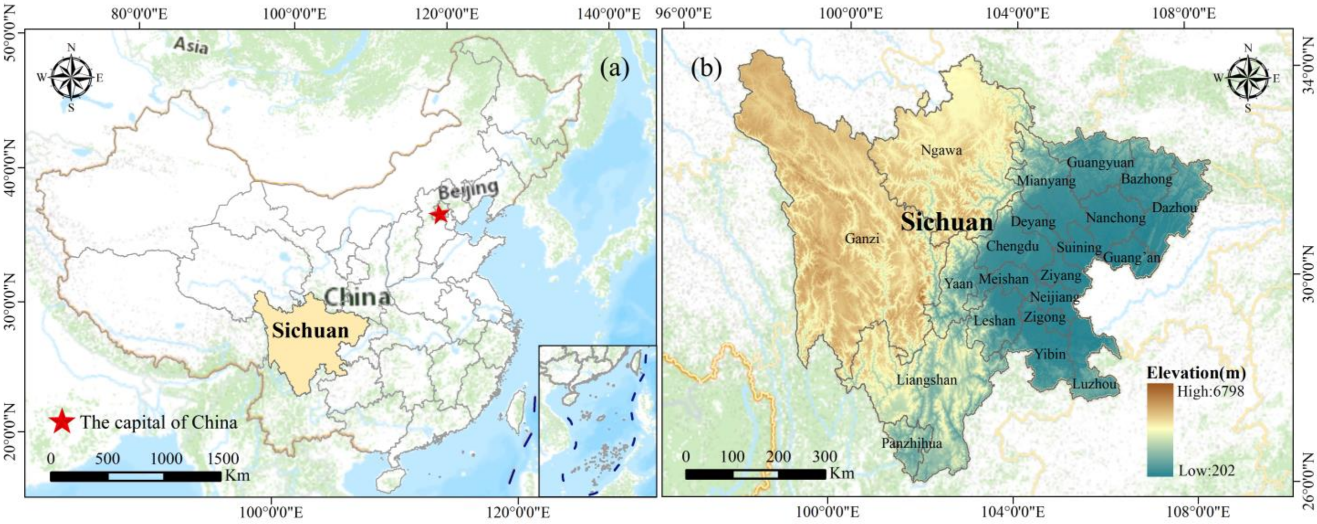

Figure 1. (**a**) Geographic location of the study area in China, (**b**) administrative units and elevation of the Sichuan Province.

3. Materials and Methods

3.1. Framework Design

In this study, we developed a comprehensive framework to enhance the understanding of the research process. The framework comprises four main steps (Figure 2): (1) the acquisition and processing of data; (2) constructing a dynamic equivalence coefficient method based on LC to evaluate the ESVs in various periods and analyze the evolution characteristics of the LC and ESVs from 2000 to 2020 in Sichuan Province; (3) simulating future LC patterns coupled with the Markov chain and the GeoSOS-FLUS model under a multi-scenario in 2025; and (4) simulating and quantifying the changes in ESVs under a multi-scenario in 2025, which will inform decision-making for ecological sustainability.

3.2. Data Source and Preprocess

The data utilized in this study are presented in Table 1. The study data consist of four main parts: (1) LC data: This study primarily focuses on monitoring changes in ESVs based on the LC before and after the implementation of major ecological protection and restoration projects. Thus, the LC serves as the core data for this study, the overall accuracy is reported to be more than 81% in numerous tests [47]. (2) ESV assessment correction data: According to the Statistical Yearbook, the proportion of dryland and paddy land in the study area is 55.7% and 44.3% of the cropland, respectively, which contributes to the construction of equivalence factors for the cropland ecosystem. The consumer price indexs (CPIs) and the yields per hectare of major crops (rice, wheat, and corn) in different years were collected to calculate the standard unit equivalent factor value. Additionally, data on net primary productivity (NPP), precipitation in the climate, and soil conservation were utilized to construct equivalents of the ESV supplied per unit area of the ecosystem in Sichuan Province based on the consideration of regional geographic variations and temporal differences. (3) Sustainable analysis data: The GDP was obtained from the statistical yearbook, which effectively reflects the level of economic development of each city. (4) LC validation and simulation data: This part of the data was obtained by selecting topographic, demographic, economic, and transportation data as driving factors, based on previous studies [48,49]. Due to the lack of public GDP data for 2020, the GDP for 2019 is used instead in this text. Traffic data is generally not publicly available, and currently, only the railway, highway, national highway, provincial highway, and county road line-types of 2020 have been collected. The Euclidean distance to the road network was calculated using ArcGIS and transportation data. With the aim of efficiency and accuracy, all the data were converted to the WGS84 coordinate system, and the spatial resolution of the raster grid was set at 1 km with consistent rows and columns through resampling.

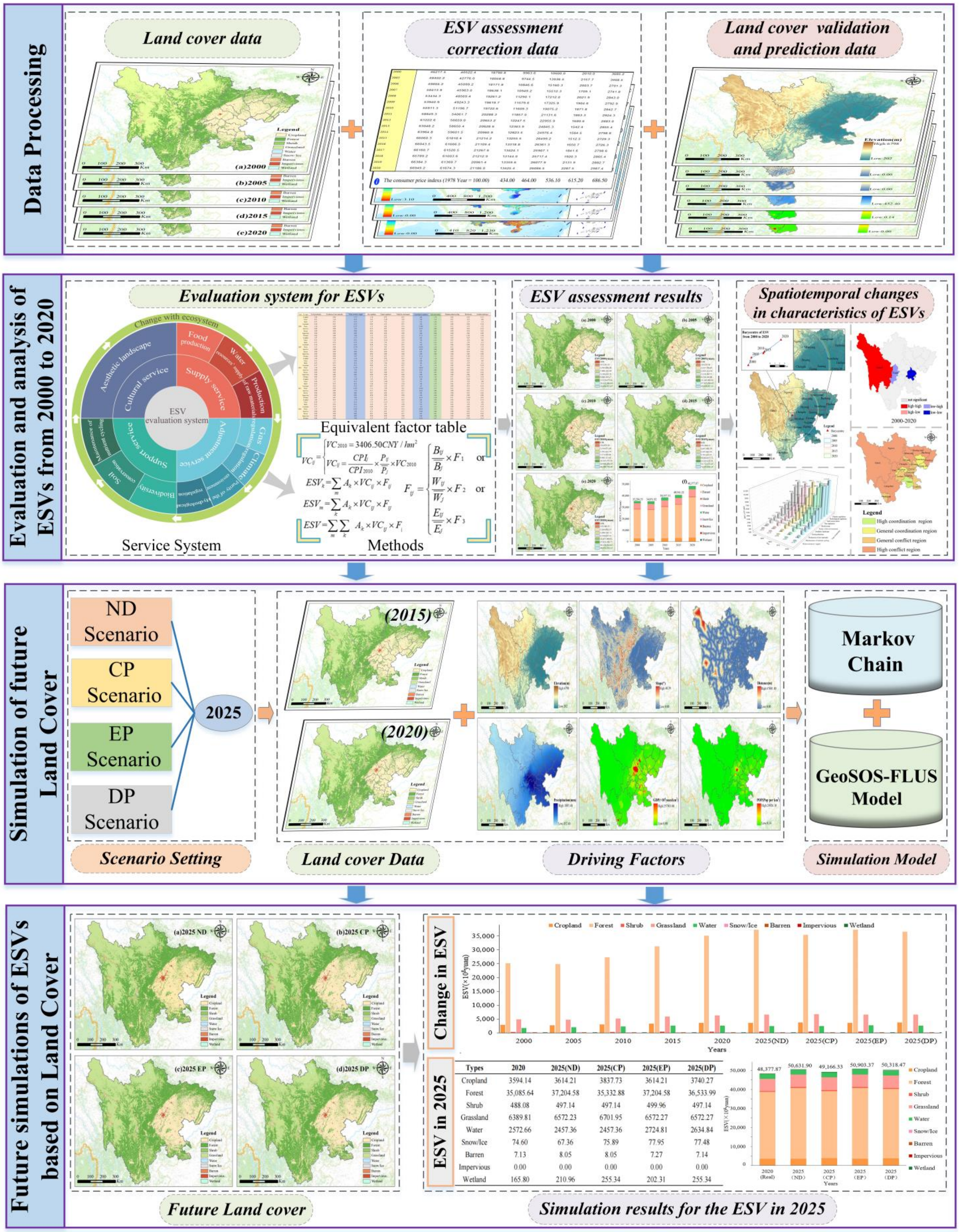

Figure 2. The research framework and processes of this study.

Table 1. Primary data information and sources.

Data Type	Data Description	Time	Source of Data	Resolution
LC data	LC can effectively record and reflect human activities and ecosystem changes.	2000, 2005, 2010, 2015, 2020	Zenodo Research Data Platform (https://www.zenodo.org, accessed on 2 July 2023)	30 m × 30 m
Statistical Yearbook data	Average yield of the major grain crops (rice, wheat, and corn), the planting area of dryland and paddy fields, and the CPI for residents in China and Sichuan Province.	2000, 2005, 2010, 2015, 2020	National Bureau of Statistics (http:www.stats.gov.cn, accessed on 5 July 2023) Sichuan Provincial Bureau of Statistics (http://tjj.sc.gov.cn, accessed on 8 July 2023)	\
Net Primary Production data	Reflect the efficiency of plant fixation and the conversion of light energy into compounds through NPP.	2000, 2005, 2010, 2015, 2020	National Earth System Science Data Center (http://www.geodata.cn/, accessed on 12 July 2023)	500 m × 500 m
Climate data	Precipitation.	2000, 2005, 2010, 2015, 2020	National Earth System Science Data Center (http://www.geodata.cn/, accessed on 17 July 2023)	1 km × 1 km
Soil Conservation data	Ability of terrestrial ecosystems to control soil erosion and protect soil functionality.	2000, 2005, 2010, 2015, 2020	Science Data Bank (https://www.scidb.cn/en, accessed on 20 July 2023)	300 m × 300 m
Topographic data	Describing terrain changes through the Digital Elevation Model (DEM) and Slope.	2019	National Cryosphere Desert Data center (http://www.ncdc.ac.cn, accessed on 1 August 2023)	1 km × 1 km
Economic data	Gross domestic product (GDP).	2010, 2015, 2019	Resource and Environment Science and Data Center (https://www.resdc.cn, accessed on 10 August 2023)	1 km × 1 km
Population data	Population (POP) in each grid cell.	2010, 2015, 2019	Resource and Environment Science and Data Center (https://www.resdc.cn, accessed on 13 August 2023)	1 km × 1 km
Traffic data	Linear road network including railways, expressways, national highways, provincial roads, and county roads.	2020	Resource and Environment Science and Data Center (https://www.resdc.cn, accessed on 20 August 2023)	\

3.3. *Evaluation Method of ESVs*

3.3.1. Calculation of the Standard Unit Equivalent Factor Value

The primary function of the equivalent value of the standard unit is to measure the potential capacity of diverse ecosystems in terms of their contribution to ecological service functions. In China, the economic value of each ecosystem value equivalent in 2010 was 3406.50 yuan/hm^2 [8,11]. To eliminate economic and geographical factors such as monetary appreciation and regional development imbalance, the standard unit equivalent factor value was newly calculated for the remaining years using the CPIs and the yields per hectare of major crops (rice, wheat, and corn), with 2010 as the base year. These parameters and standard unit equivalent factor values are listed in Table 2.

$$VC_{ij} = \begin{cases} VC_{2010} = 3406.50\ \text{yuan/hm}^2 \\ VC_{ij} = \frac{CPI_j}{CPI_{2010}} \times \frac{P_{ij}}{\overline{P_j}} \times VC_{2010} \end{cases} \quad (1)$$

where VC_{ij} denotes the standardized unit equivalent factor value of region i in year j, and VC_{2010} represents the standardized unit equivalent factor value of China in 2010. CPI_j and CPI_{2010} represent the consumer price index of China in year j and 2010, respectively. P_{ij} and p_j refer to the average grain production of region i and China in year j, respectively.

Table 2. Calculation parameters and correction results of the standard unit equivalent factor value.

Year	Average Grain Production in China (kg/hm^2)	Average Grain Production in Sichuan Province (kg/hm^2)	CPI (*1978 Year = 100.000*)	Standard Unit Equivalent Factor Value of China (Yuan/hm^2)	Standard Unit Equivalent Factor Value of Sichuan Province (Yuan/hm^2)
2000	4753.000	5596.194	434.000	2757.734	3246.962
2005	5225.000	5687.666	464.000	2948.360	3209.433
2010	5528.000	5797.333	536.100	3406.500	3572.470
2015	5989.000	5689.742	615.200	3909.119	3713.789
2020	6296.000	5943.111	686.500	4362.175	4117.677

3.3.2. Revision of the ESV Equivalent Factor Table

According to numerous studies [8,50,51] on the definition and classification of ecological functions, the main hierarchical structure of ecosystem services can be summarized as shown in Figure 3. The structure and appearance of ecosystems undergo continuous changes in various regions and time periods, resulting in fluctuations in the ESs they offer and their corresponding value. In this regard, we refer to related studies for the correction of dynamic rationalization through NPP, precipitation, and soil and water conservation data [8,49]. The correction results of the study area as listed in Table A1.

$$F_{ij} = \begin{cases} \frac{Bij}{\overline{Bj}} \times F_1 & \text{or} \\ \frac{Wij}{\overline{Wj}} \times F_2 & \text{or} \\ \frac{Eij}{\overline{Ej}} \times F_3 \end{cases} \tag{2}$$

where F_{ij} refers to the dynamic equivalent factor per unit area for an ecosystem service in region i in year j; B_{ij}, W_{ij}, and E_{ij} refer to the average net primary production, the annual average precipitation, and the annual average amount of soil conservation in region i in year j, respectively; and $\overline{B_j}$, $\overline{W_j}$, and $\overline{E_j}$ represent the corresponding average values in China. Specifically, F_1 includes the ESs of food production, the production of raw materials, gas regulation, climate regulation, the purity of the environment, the maintenance of nutrient cycling, biodiversity, and the aesthetic landscape; F_2 includes the ESs of the water resources' supply and hydrological regulation; and F_3 includes the ESs of soil conservation.

3.3.3. Calculation of ESV

The regional ESV is calculated using the following formula:

$$ESV_k = \sum_m A_k \times VC_{ij} \times F_{ij} \tag{3}$$

$$ESV_m = \sum_k A_k \times VC_{ij} \times F_{ij} \tag{4}$$

$$ESV = \sum_m \sum_k A_k \times VC_{ij} \times F_{ij} \tag{5}$$

where ESV_k, ESV_m, and ESV denote the ESV of LC form k, the ESV of function type m, and total the overall ESV, respectively; A_k represents the area (hm^2) for LC form k.

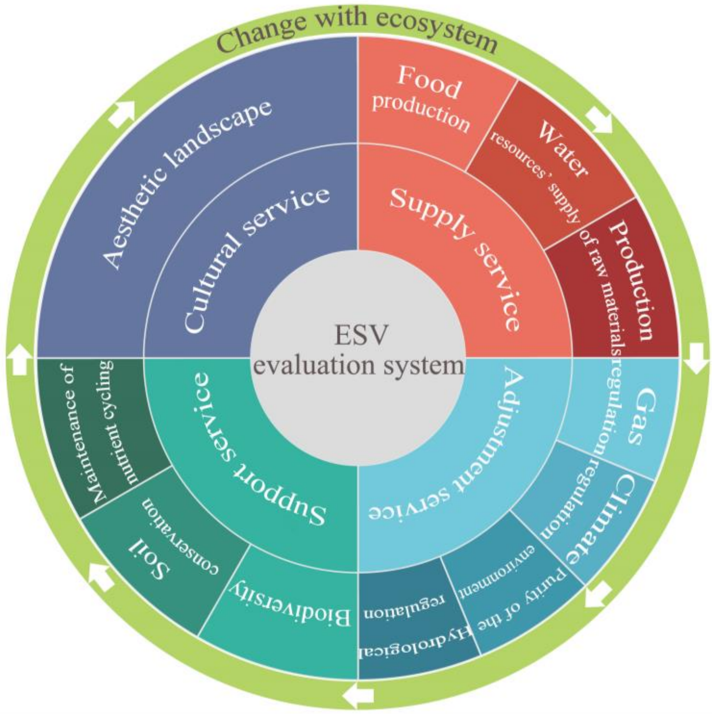

Figure 3. Schematic representation of the hierarchical structure of major ecosystem services.

3.4. Analysis of the Evolution of the Characteristics of ESV

3.4.1. Analysis of the Evolution of the Characteristics of the ESV

The concept of the barycenter holds significance in physics. The trajectory of the geographic barycenter can effectively help determine the state and direction of the offsets observed in the time series [52]. The geographic barycenter model was utilized to demonstrate the spatial variation of the ESVs, and the coordinates are provided below:

$$X_t = \frac{\sum_{i=1}^{n} E_{ti} \times X_i}{\sum_{i=1}^{n} E_{ti}} \quad (6)$$

$$Y_t = \frac{\sum_{i=1}^{n} E_{ti} \times Y_i}{\sum_{i=1}^{n} E_{ti}} \quad (7)$$

where X_t and Y_t denote the longitude and latitude coordinates of the ESV's geographic barycenter in year t, respectively; n is the number of spatial units; X_i and Y_i are the center coordinates of area i; and E_{ti} is the ESV of area i. The standard deviation ellipse (SDE) is an effective method for assessing the centrality, distribution, directionality, and spatial form of the ESV's spatial distribution [53,54]. In this study, we analyzed the spatial dispersion and directional trend of the ESV more easily by utilizing the SDE.

3.4.2. Spatial Heterogeneity of the ESV

The Global Moran Index (GMI) is an effective method for analyzing the spatial characteristics of an ESV. When the GMI is greater than 0, it indicates a positive spatial autocorrelation of an ESV across regions, and vice versa for a negative correlation. A larger index signifies a stronger spatial aggregation of the evaluation results [55].

$$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(x_i - \overline{x})(x_j - \overline{x})}{S^2 \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}} \quad (8)$$

$$S = \frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})^2 \quad (9)$$

where n is the number of spatial units; x_i and x_j are the ESVs for units i and j, respectively; and W is the spatial weight matrix. If units i and j are adjacent, then $W = 1$, otherwise, $W = 0$.

3.4.3. Coupled Analysis of ESV and Sustainable Development

In addition to examining the characteristics of spatiotemporal changes, we also employ an alternative method to study and analyze the interconnection between coordinated development and ESV. Based on the connotation of the ecological environment and economic development, the coordinated relationship is analyzed by constructing the Year of Economy-Environmental Harmonize (YEEH) index [56]. The specific formula is as follows:

$$YEEH = \frac{ESV_{ij}}{GDP_{ij}} \quad (10)$$

where ESV_{ij} and GDP_{ij} denote the amount of the ESV and the amount of gross regional product in year j in region i, respectively; it is generally considered that when $0 \leq YEEH < 0.3$ and $YEEH \geq 1.8$, there is high conflict in the region; when $0.3 \leq YEEH < 0.6$ and $1.5 \leq YEEH < 1.8$, there is general conflict in the region; when $0.6 \leq YEEH < 0.9$ and $1.2 \leq YEEH < 1.5$, there is general coordination in the region; and when $0.9 \leq YEEH < 1.2$, there is a high amount of coordination in the region.

3.5. Simulation of Future Land Cover

3.5.1. Markov Chain Model

The Markov chain model is a time domain stochastic model that mainly predicts the probability of event occurrence [57]. Markov processes are stochastic processes that involve transitions between states in a state space. The changes in LC are often considered to follow a Markov process, making Markov chain models a popular choice for predicting future LC with high accuracy [58,59]. Based on historical data, the Markov transfer probability matrix and transfer state of LC are expressed by the following equation [60]:

$$P_{ij} = \begin{bmatrix} P_{11} & \cdots & P_{1n} \\ \vdots & \ddots & \vdots \\ P_{n1} & \cdots & P_{nn} \end{bmatrix} \quad (11)$$

$$P_{ij} \in [0,1] \; and \sum_{i=1,j=1}^{n} P_{ij} = 1, (i,j = 1,2,\ldots,n) \quad (12)$$

$$S_{t+1} = P_{ij} \times S_t \quad (13)$$

where P_{ij} is the transition probability matrix that demonstrates the probability of LC type i changing to LC type j; S_{t+1} and S_t indicate the LC at time t and t + 1, respectively.

3.5.2. Scenario Setting

According to the current situation and development policies of China, we propose four development scenarios: a natural development (ND), cropland protection (CP), ecological protection (EP), and a cropland and ecological dual protection (DP). These scenarios are determined by the demand for land conversion under different circumstances and with specific constraints. The conversion cost matrix for each scenario is depicted in Figure 4.

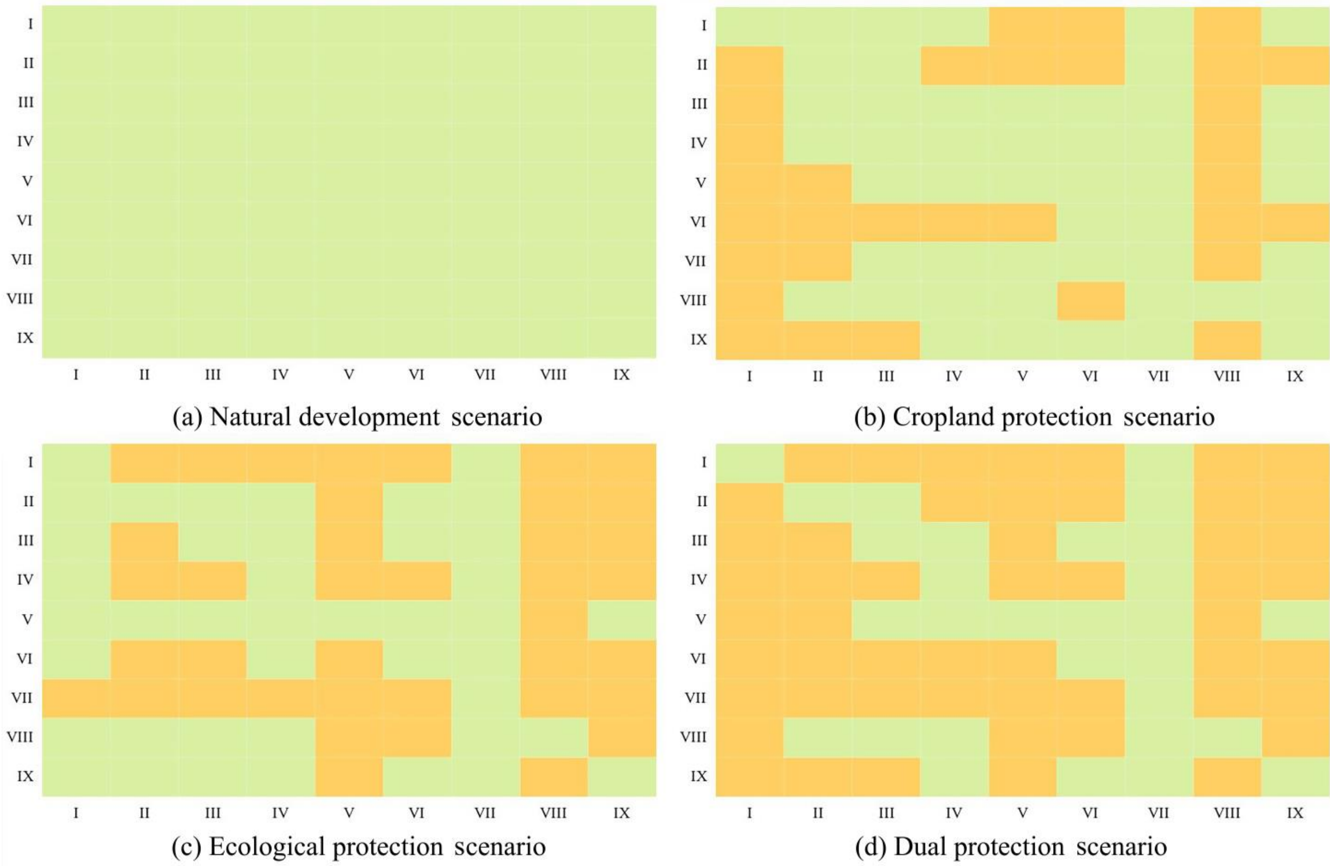

Figure 4. Conversion cost matrix (the numbers from I to IX represent cropland, forest, shrub, grassland, water, snow/ice, barren, impervious, and wetland. The horizontal and vertical rows indicate the current and future LC, respectively, with green representing those that are convertible and yellow representing those that are non-convertible).

The NG scenario was set to assume that the evolution of the different LCs follows the laws of nature. It assumes that these LCs will not be influenced by policy adjustments during development and that all LCs can be converted into one another.

The CP scenario was set to emphasize the preservation of cropland and the maintenance of the red line of cropland. It is prohibited to convert cropland into another LC type, while other land can be converted into cropland. Additionally, a few specific conditions that cannot be transferred have been established based on past experience.

The EP scenario was set to prioritize ecological preservation and classifies LC based on its ecological benefits. The ranking order is as follows: water, wetland, forest, shrub, snow and ice, grassland, cropland, barren, and impervious [8]. The criterion for conversion is that ecologically efficient lands are denied conversion to ecologically inefficient lands, with the exception of those that are impervious.

The DP scenario was set to achieve a balance between cropland protection and ecological protection. It is crucial to prevent the conversion of cropland into other land types while allowing the other land types to be converted into cropland. Additionally, it is important to prohibit the conversion of land with a high ecological benefit into that with a low ecological benefit.

3.5.3. GeoSOS-FLUS Model

The GeoSOS-FLUS model is a recently developed LC change simulation model designed to simulate various LC change scenarios considering the combined influence of humans and nature. It has a wheel-based adaptive inertia competition mechanism that can deal with the uncertainties and complexity of the interaction between various LCs [29]. Currently, this method has been widely used in LC simulations and urban expansion simulations [49]. The model consists of two parts: (1) The probability of occurrence estimation module based an ANN. This module can explore the complex relationship between input data and training objectives through extensive learning recall iterations. In this study, we assessed the probability field of LC suitability for 2015 and 2020 by considering natural influences such as slope and elevation, meteorological influences like precipitation, and socio-economic factors including population, GDP, and the distance from different types of roads. These factors can reflect the construction land intensity, growth land consumption, development flexibility, and the contribution of the population and the economy, and are forward-looking and instructive indicators of future lands' layout and evolution [61]; (2) The roulette selection based self-adaptive inertial competition mechanism CA module. The stochastic nature of the module allows the model to reflect the uncertainty and alternation of actual LC change, which better accounts for competition between different LCs. The expansion capacity of each LC is determined by the neighborhood factor, which ranges from 0 to 1 and indicates the ability of different LC types to expand. LC types closer to 1 generally have a greater expansion capacity. In this study, existing research findings [49,62] and expansion capacity characteristics were adopted to determine the model's neighborhood factors (Table 3).

Table 3. Neighborhood factor parameters for different LCs under different scenarios.

LC	Cropland	Forest	Shrub	Grassland	Water	Snow/Ice	Barren	Impervious	Wetland
ND	0.5	0.4	0.3	0.5	0.2	0.1	0.2	1.0	0.2
CP	0.8	0.4	0.3	0.5	0.2	0.1	0.2	0.4	0.2
EP	0.3	0.7	0.6	0.8	0.4	0.2	0.1	0.3	0.3
DP	0.65	0.55	0.45	0.65	0.3	0.15	0.15	0.35	0.25

3.6. Model Validation

To better compare our simulation results with those of previous studies, both the kappa coefficient and the figure of merit (FOM) are adopted to judge the accuracy of the simulation. As an indicator of interrater reliability, the kappa coefficient is adopted to measure the agreement between the simulation and the reference. Ranging from 0 to 1, a larger kappa coefficient represents a higher overall simulation accuracy and 0.75 is usually considered as a threshold for high simulation accuracy [20,60]. The FOM is also a metric utilized to assess the precision of simulation modifications. A higher FOM value suggests a more accurate simulation. Typically, FOM values do not have a set range and generally fall below 0.3 [49].

3.7. Future Simulations of ESVs Based on LC

Exploring the future spatiotemporal patterns of ESVs is crucial for the harmonious development of the economy, society, and nature. In this study, we introduced the autoregressive integrated moving average (ARIMA) model [63] provided of SPSS Statistics version 25.0 software to predict the future standard unit equivalent factor value. Li et al.'s studies [64] have found that changes in LC can affect the soil conservation function. Consequently, the ESV equivalent factor table for 2025 was constructed by considering trends in soil conservation, the average NPP, and the average precipitation over previous years. Building upon this research, future ESVs based on LC will be simulated.

4. Results and Analysis

4.1. Spatiotemporal Evolution of LC

4.1.1. Overall Characteristics of LC Changes

In this study, the statistical analysis and graphical presentation were conducted using ArcGIS, based on historical data of LCs. The LC type statistics for the years 2000, 2005, 2010, 2015, and 2020 reveal that the most extensive category was forest, covering an area of over 186,000 km^2, which represents approximately 39.15% of the study area. Grassland and cropland follow with areas of more than 160,000 km^2 and 112,000 km^2, respectively, accounting for about 33.53% and 24.05% (Table 4). The remaining LCs have smaller areas, and their ranking based on area varies in different years. During the 20-year period, the areas that were impervious and made up of forests exhibited a noticeable upward trend, with forests covering an additional 9748 km^2 and impervious land expanding by 2537 km^2. Nevertheless, it is worth noting that the rate of forest growth experienced a decline during the periods from 2005 to 2010 and 2010 to 2015, which is consistent with existing studies [65]. On the other hand, the shrub, water, barren, and wetland categories have alternated, but generally demonstrated increasing trends. Notably, barren land has experienced an increase of 1298 km^2. In contrast, cropland and grassland have consistently decreased in size, accumulating reductions of 8370 km^2 and 5467 km^2, respectively. This conclusion has been validated in existing studies [66]. Additionally, the snow/ice category has shown an overall decreasing trend, with a reduction of 286 km^2.

Table 4. The change process of time series in the LCs of the study area from 2000 to 2020 (km^2).

LC	2000	2005	2010	2015	2020	2000–2005	2005–2010	2010–2015	2015–2020
Cropland	120,404	118,591	117,313	116,192	112,034	−1813	−1278	−1121	−4158
Forest	186,050	188,366	190,201	190,905	195,798	2316	1835	704	4893
Shrub	4091	3938	4256	4257	4123	−153	318	1	−134
Grassland	165,661	164,379	162,847	161,736	160,194	−1282	−1532	−1111	−1542
Water	2690	3335	3546	3417	3178	645	211	−129	−239
Snow/Ice	1427	1465	1499	1590	1141	38	34	91	−449
Barren	3345	3501	3159	3906	4643	156	−342	747	737
Impervious	1899	2320	2974	3827	4436	421	654	853	609
Wetland	434	106	206	171	454	−328	100	−35	283

4.1.2. Structural Realignment Change in LC

Figure 5 illustrates the relationship between structural transformations of LC from 2000 to 2020, mainly reflecting the pattern of change over time. The most common inter-transferences occurred among cropland, forest, and grassland, with the highest rate being observed between forest and cropland. The increase in forest areas was primarily attributed to cropland and grassland, while the depletion of forest areas was mainly associated with cropland and shrubs. This conclusion is consistent with existing studies [65]. The decrease in the amount of cropland is not solely attributed to urban development and construction, but also to the significant impact of the project aimed at restoring farmland to forest and grassland. The new additions of the impervious and wetland categories are primarily derived from cropland and grassland, respectively. On the other hand, the barren category is mainly transferred from grassland and snow/ice.

4.2. Spatiotemporal Change in ESVs in Sichuan Province

4.2.1. General Characteristics of Spatiotemporal Variations in ESVs

Over the 20-year period, the ESV increased significantly from 35,294.55 × 10^8 yuan in 2000 to 48,377.87 × 10^8 yuan in 2020, indicating a substantial overall increase of 13,083.32 × 10^8 yuan (Figure 6). However, there was a diminutive decrease in the ESV in 2005 compared to 2000. In terms of spatial distribution, the ESV exhibits clear regional differentiation, with higher values observed in the western high mountain and hilly regions compared to the eastern plains region. Additionally, there are scattered areas with zero ESV, and the extent of these areas is gradually increasing.

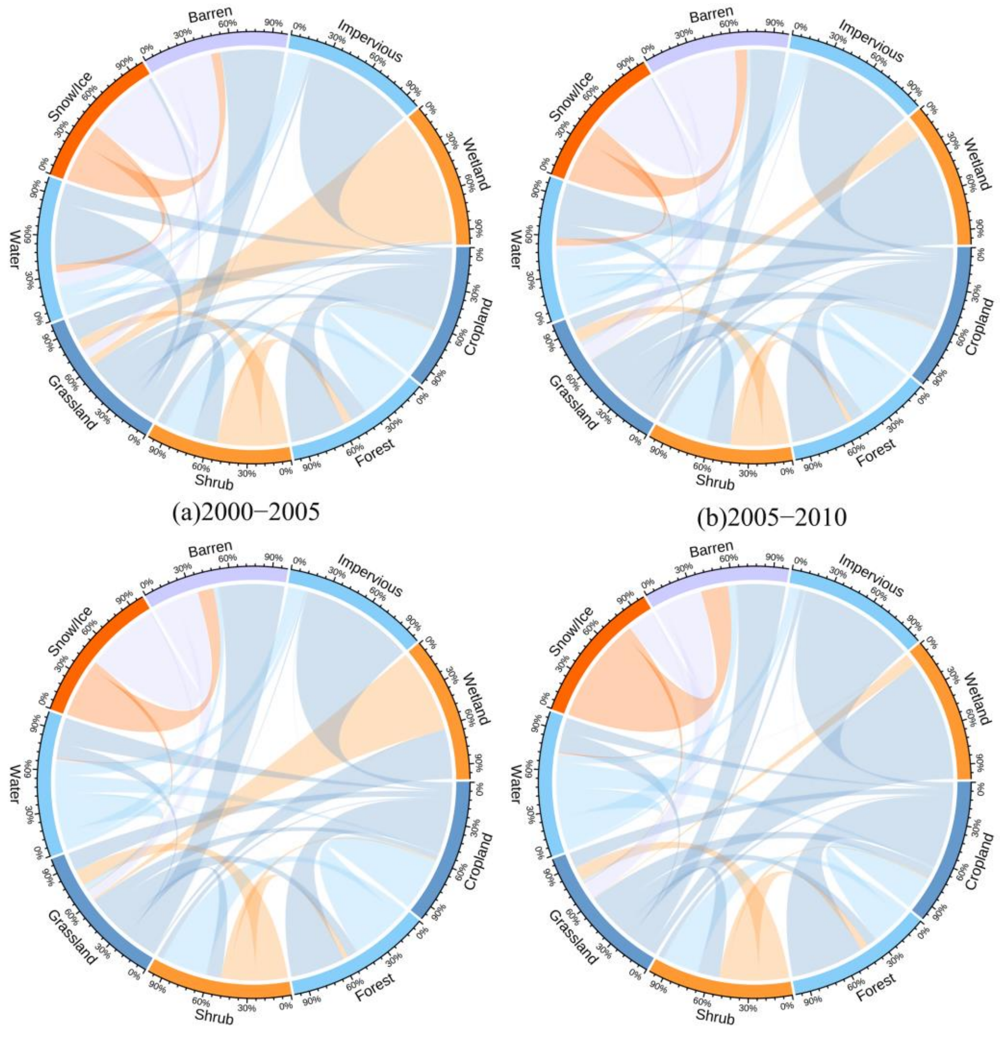

Figure 5. Transfers and changes in LC in the study area during different time periods.

In terms of the values of different ecosystems, the forest was the major contributor to the ESV from 2000 to 2020, accounting for approximately 71.48%. This was followed by grassland, agricultural land, watershed, and shrubs, which accounted for about 13.60%, 7.80%, 5.67%, and 1.03%, respectively. Meanwhile, except for the impervious areas, the ESV of the remaining LC categories showed varying degrees of increase. Among them, forests and grasslands experienced the highest increase in ESV, with an average of 496.52 $\times$ 10^8 yuan/year and 70.98 $\times$ 10^8 yuan/year, respectively. Despite the fact that the ESV of the impervious areas is zero and continues to safeguard economic and social development through encroachment on other ecological spaces, the overall ESV remains relatively stable and is growing. This result is closely related to the implementation of major ecological protection and restoration projects such as protecting natural forest resources, constructing the shelterbelt system, and returning grazing land to grassland.

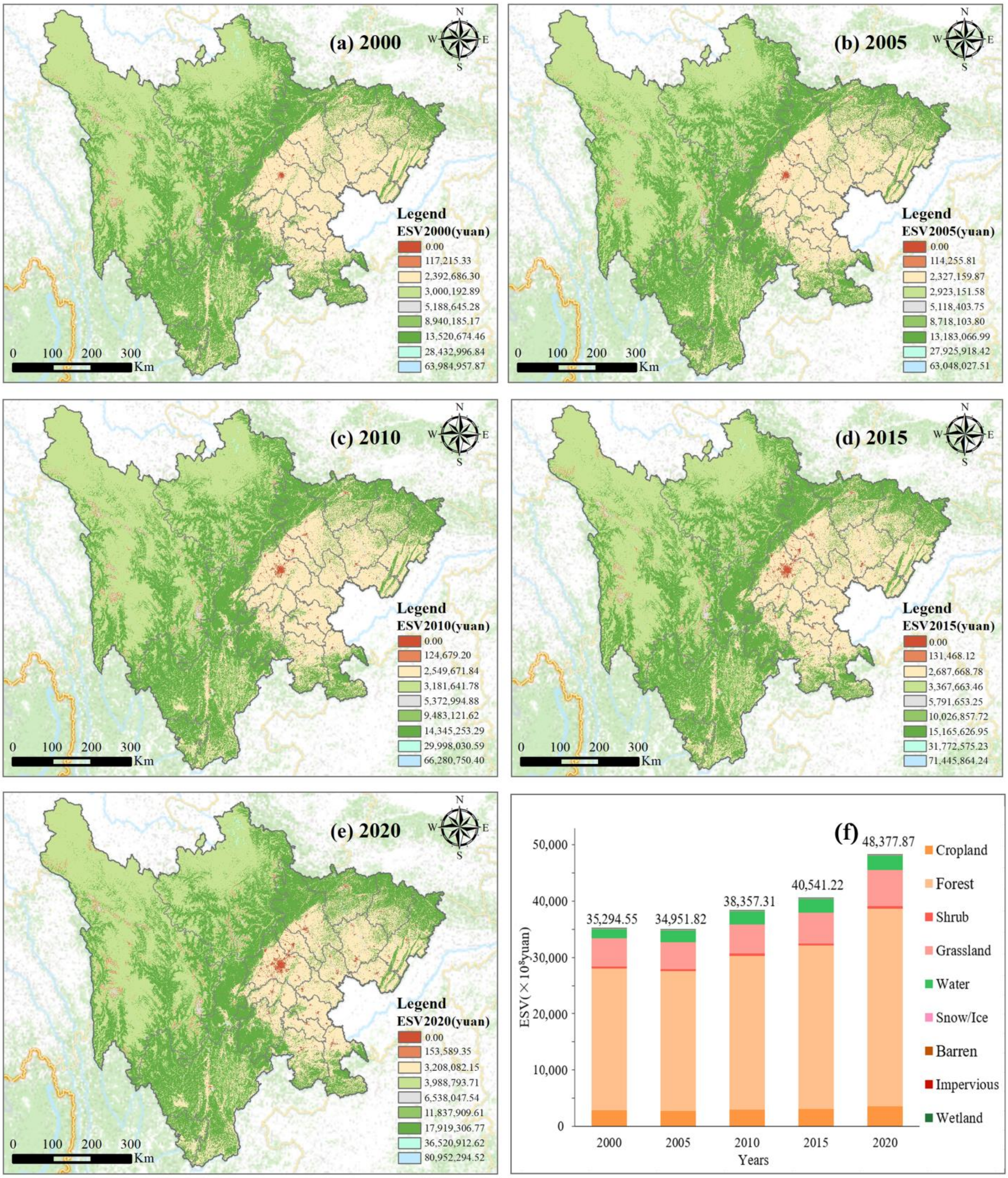

Figure 6. (**a**–**e**) Spatial pattern of ESVs in Sichuan Province for 2000, 2005, 2010, 2015, and 2020 at a 1 km grid scale, (**f**) total and composition of ESVs in different years.

The state and orientation change characteristics of the ESVs were analyzed using ArcGIS, and the results were presented as standard deviation ellipses of the barycenter position. The barycenter for the ESVs was found to be located in the northeast of Ya'an, Sichuan Province. Over the period from 2000 to 2020, the barycenter of the values exhibited an overall trend of moving towards the northeast, with a cumulative movement of 9.25 km (Figure 7). Notably, the barycenter of the values showed the greatest movement from 2015 to 2020, indicating a significantly higher growth of ESV in the northeast part of the study area compared to the northwest part. The standard deviation ellipse results reveal that the spatial distribution of the ESVs is primarily oriented in the north–south direction, with a relatively stable distribution pattern and no significant clustering effect. Additionally, the direction of the standard deviation ellipse aligns with the development direction of the ecological corridor in the land space planning of Sichuan Province, underscoring the importance of ecological corridor construction for enhancing regional ESV.

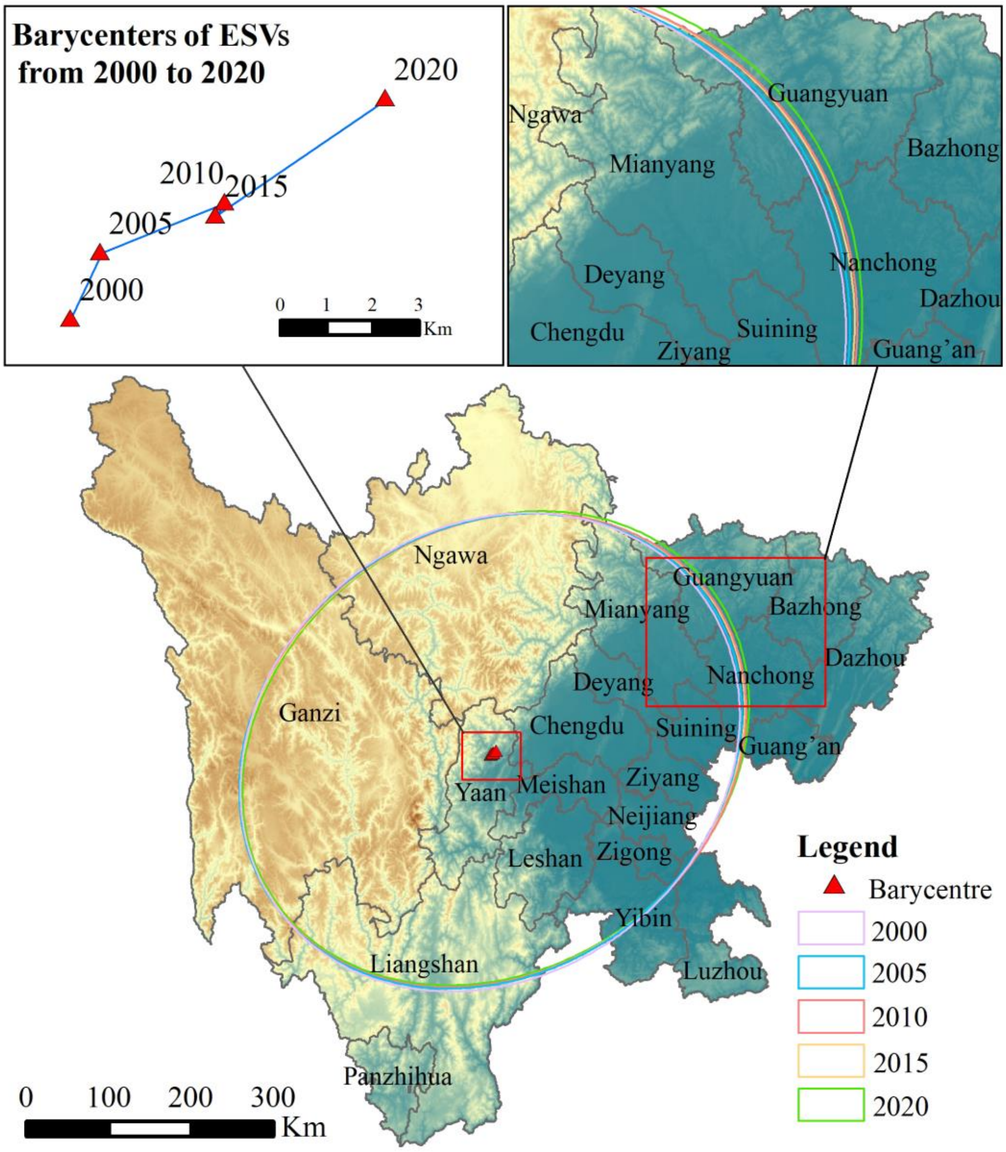

Figure 7. Trajectories of movement of the barycenters and standard deviational ellipses of ESVs from 2000 to 2020.

4.2.2. Analysis of Changes in ESV for Different Ecological Service Functions

The ESVs for each ecological service function classification were counted and the changes are illustrated through Figure 8. When examining the service functions of different ecosystems, all ecological service functions exhibited an increasing trend in ESV. The three functions of climate regulation, hydrological regulation, and soil conservation were found to be the most valuable, accounting for approximately 23.63%, 21.33%, and 18.80%, respectively. These functions experienced increases of 2463.52 $\times$ 10^8 yuan, 2469.77 $\times$ 10^8 yuan, and 4441.41 $\times$ 10^8 yuan, respectively. The water resources' supply and nutrient cycling maintenance are the two services that have shown the lowest increase in value, both below 100 $\times$ 10^8 yuan. However, when considering the rate of increase, the soil conservation function stands out with a cumulative increase of 75% compared to that in 2000. This significant increase can be attributed to the implementation of various conservation and ecological restoration projects. By planting forests, grasslands, and other vegetation, their well-developed root systems help stabilize the soil, while the accumulation of fallen leaves and other materials effectively minimizes the impact of surface water, thus preventing soil erosion. For instance, in 2014, the sediment output at the end section of the Yalong River decreased by 62%, and at the Wutongqiao hydrological station of the Minjiang River, it decreased by 47% compared to that in 1999. In 2015, the province's ecological resources, including its natural forests, planted forests, farmland forests, grasslands, and wetland vegetation, reduced the soil loss by 126 million tons. These results demonstrate the remarkable success of projects such as the constructing of the shelterbelt system in preventing soil erosion and reducing desertification.

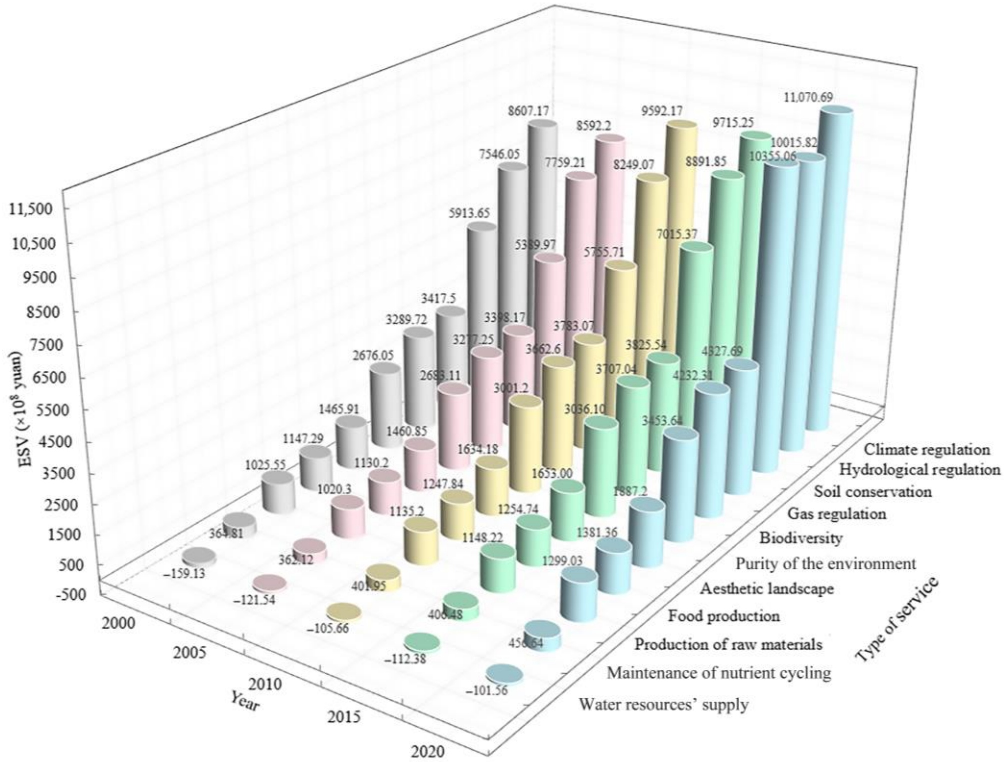

Figure 8. Change in process of time series in ESVs of each ecological service function from 2000 to 2020 (Note: Colors represent different years).

4.2.3. Analysis of Changes in ESV in Prefecture-Level Cities

In terms of the total ESV in different cities (Table 5), Ganzi, Ngawa, and Liangshan are ranked among the top three cities and significantly surpass other cities. The cities of Neijiang, Ziyang, and Zigong ranked in the bottom three positions among all cities, with none of their ESV totals exceeding 300 $\times$ 10^8 yuan. In terms of the ESV growth in different cities, Nanchong experienced the highest increase of 65.60%, followed by Suining, Guangyuan, and Bazhong with 63.21%, 60.08%, and 54.48%, respectively. On the other hand, Luzhou had the lowest growth among all the cities, with an increase of only 17.06%.

Based on the analysis of Figure 9a–e, it can be observed that the Global Moran's p-value of the ESV for each city from 2000 to 2020 is 0.1, indicating a successful passing of the significance test. Throughout the study period, the overall Moran's index of the ESV in each city remains consistently above 0.3, suggesting a strong positive spatial autocorrelation and noticeable spatial aggregation characteristics of the ESV. The spatial distribution depicted in Figure 9f further confirms that the aggregation pattern of the ESV in each city remains consistent and unchanged over the 20-year period. Notably, the primary high–high aggregation area is Ganzi, which is attributable to its role as a pioneer and key area in the implementation of the natural forest resources protection project. Starting from September 1998, the Ngawa, Ganzi, and Liangshan cities have actively managed and protected 19,234,200 hm^2 of existing natural forests as part of the natural forest resource protection project [67]. Additionally, from October 1999 onward, these cities have also been at the forefront of the restoration of grazing land to grassland project in the northwestern and southwestern areas of Sichuan Province. The abundant distribution of forests and grasslands in these areas has contributed to the relatively better ecosystem cycle and environmental development of Ganzi and its neighboring Ngawa and Liangshan, effectively ensuring the stability of their ESVs. Conversely, Ya'an stands as the sole city in the low–high agglomeration area, indicating a negative spatial autocorrelation between Ya'an and its surrounding areas. Lastly, the low–low agglomeration area is predominantly occupied by the Zigong and Neijiang cities, where the degradation of ESs and the imbalance of development hinder the enhancement of the ESV, demanding greater attention in the future.

Table 5. Total ESV of each city in Sichuan Province for 2000, 2005, 2010, 2015, and 2020 and ESV changes from 2000 to 2020.

City	Total ESV ($\times 10^8$ Yuan)					Changes in ESV from 2000 to 2020 ($\times 10^8$ Yuan)	Changes in ESV from 2000 to 2020 (%)
	2000	2005	2010	2015	2020		
Ngawa	6069.38	5982.87	6524.40	6856.82	8174.79	2105.41	34.69
Bazhong	1017.72	1084.33	1204.12	1263.03	1572.14	554.42	54.48
Chengdu	734.23	705.23	723.97	797.94	980.15	245.92	33.49
Dazhou	1296.00	1285.89	1521.25	1523.83	1914.74	618.74	47.74
Deyang	288.81	283.27	306.28	328.49	403.40	114.59	39.68
Ganzi	9097.16	9127.01	9963.20	10,456.28	12,244.10	3146.94	34.59
Guang'an	306.03	310.79	355.46	379.79	438.57	132.54	43.31
Guangyuan	1419.56	1454.17	1621.23	1784.49	2272.49	852.93	60.08
Leshan	1208.23	1154.17	1268.62	1384.77	1629.63	421.4	34.88
Liangshan	5909.46	5773.75	6300.40	6717.81	7955.36	2045.9	34.62
Luzhou	1096.80	1037.60	1126.11	1145.66	1283.96	187.16	17.06
Meishan	421.32	399.41	439.85	477.88	564.29	142.97	33.93
Mianyang	1705.23	1663.12	1827.48	1949.99	2373.70	668.47	39.20
Nanchong	510.32	579.16	678.99	692.16	845.07	334.75	65.60
Neijiang	196.53	192.41	218.73	239.80	284.38	87.85	44.70
Panzhihua	798.01	774.76	828.36	856.64	995.11	197.1	24.70
Suining	211.45	212.51	248.86	266.51	345.11	133.66	63.21
Ya'an	1658.05	1645.16	1794.51	1909.33	2270.15	612.1	36.92
Yibin	987.37	927.59	1000.76	1084.98	1311.45	324.08	32.82
Ziyang	197.21	196.23	221.22	230.18	281.21	84	42.59
Zigong	165.68	162.39	183.51	194.84	238.07	72.39	43.69
Average	1680.69	1664.37	1826.54	1930.53	2303.71	623.02	37.07

The annual YEEH index is calculated to assess the coordination between the regional ESV and GDP. The spatial distribution of the YEEH index varies significantly across different stages, with a higher number of conflict cities than coordination cities, in general (Figure 10). Analyzing the YEEH across five different time periods, we consistently found highly conflicting regions in the cities of Ganzi, Ngawa, Liangshan, Ya'an, Bazhong, and Guangyuan. These cities have experienced much higher ecological benefits compared to their economic development from 2000 to 2020, resulting in a low degree of coordination. On the other hand, Chengdu and its neighboring cities such as Deyang have transitioned from coordination cities to conflict cities. These cities have focused on economic development while neglecting the growth of their ESV, leading to uncoordinated development. It is notable that Panzhihua and Bazhong have shown a continuous positive trend in the coordination between their ecological environment and economic development, and their paths can serve as valuable references.

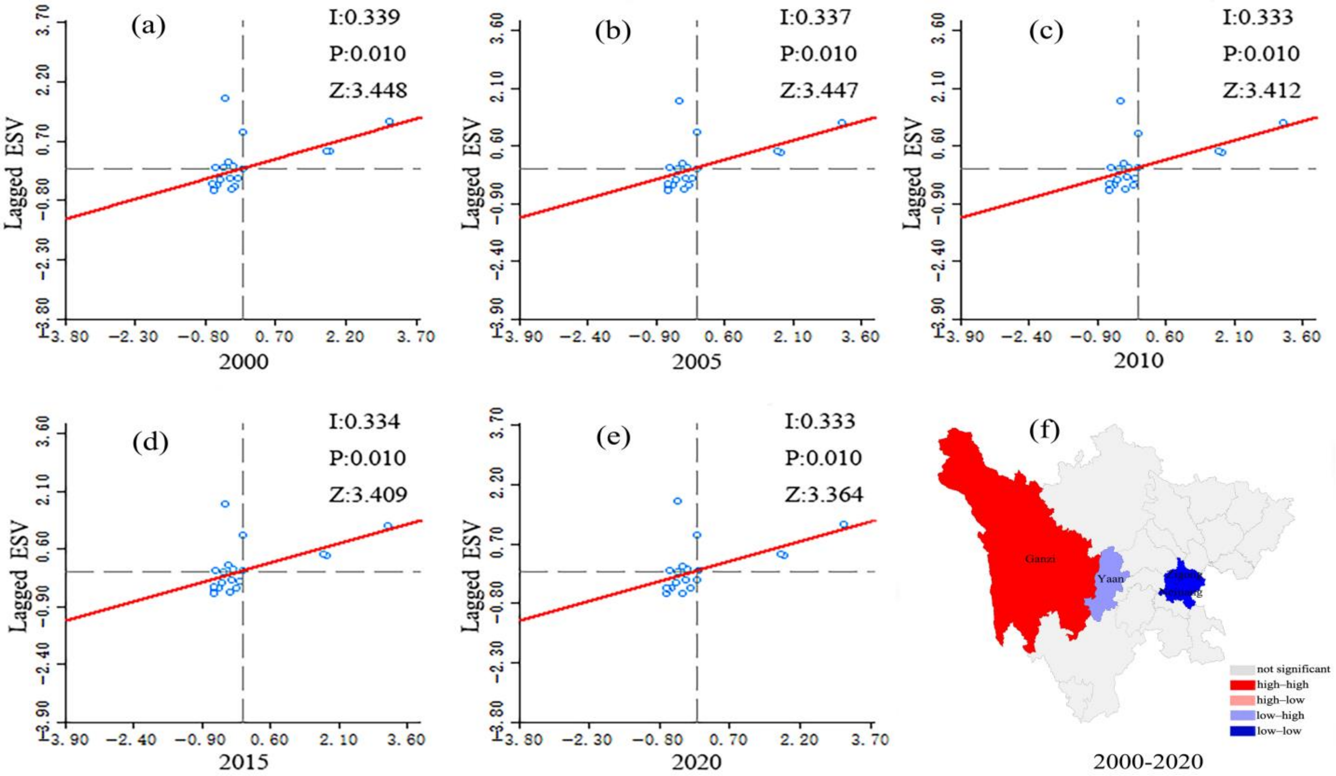

Figure 9. Results of spatial autocorrelations of total ESV by cities from 2000 to 2020. (**a**–**e**) Representations of the Moran Scatter Plots of ESV changes in different periods, by circle and line to represent the city samples and aggregated trends respectively. (**f**) Representations spatial results.

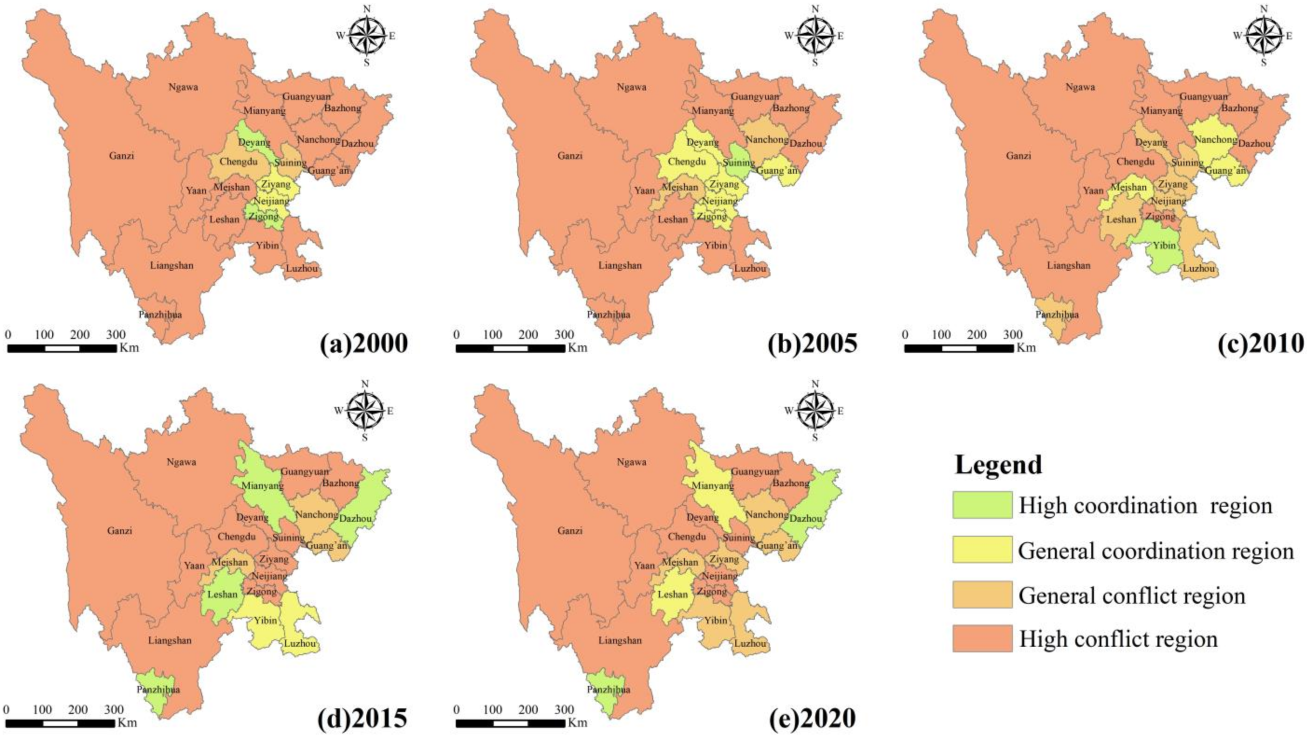

Figure 10. Processes of change in the spatiotemporal sequence of economic and environmental harmonization across cities.

4.3. Multi-Scenario Simulation of LC and ESV

4.3.1. Validation of the GeoSOS-FLUS Model

To evaluate the accuracy of the Markov Chain model for future LC demand and the credibility of the FLUS model, the simulation results in 2020 were compared with the real LC typology in 2020 using the FOM and kappa test with a sampling ratio of 5%. The results indicate a strong agreement between the simulation results and the real LC pattern in 2020. The kappa coefficient and the overall accuracy reach 0.91 and 94% on average under the four scenarios, respectively. The FOM value ranged around 2.67% on average, which is near the standard level for such simulations [20]. This proves that the simulation accuracy meets the requirements, and the model can realistically describe the future LC change pattern in Sichuan Province to support the prediction of ESVs.

4.3.2. Future LC modeling with Different Scenarios

Figure 11 presents the simulation results of the spatial distribution of LC in 2025 under four different scenarios. In the ND scenario, the areas of forests, impervious areas, barren areas, and wetlands show an increasing trend compared to 2020, while cropland decreases, which aligns with current spatiotemporal trends. However, the decrease in cropland by 3776 km^2 (3.37%) contradicts China's current policy of cropland protection [68]. In the CP scenario, there is a significant increase in the area of cropland, with a rise of 2919 km^2 (2.61%) compared to 2020, which is more consistent with the original intention. However, this increase in cropland leads to decreases in the forest, shrub, and water categories, which align with the goal of protecting cropland. The EP scenario exhibits an increasing trend for important ecosystems such as water, wetland, and forest areas, with increases of 2.29%, 18.5%, and 3.87%, respectively. This scenario better protects LCs with ecological functions. In the DP scenario, there is no decrease in the area of cropland, but barren land decreases by 4.31%. This scenario achieves the harmonious development of humans and nature by increasing the areas of woodlands, waters, and wetlands with high ecological values while ensuring the area of cropland remains constant. The impervious areas in the four scenarios also show increases of different magnitudes, which emphasizes ensuring food security and ecological construction while also taking into account economic development, indicating that the scenarios' settings are in line with reality.

4.3.3. ESV Assessment Based on Future LC Simulations

We predicted a standard unit equivalent factor value of 4245.80 yuan/ha for the study area in 2025 based on the ARIMA model, with an R^2 of 0.909, indicating its suitability for future ESV prediction. Figure 12 illustrates the projected ESV results for Sichuan Province in 2025 under four different development scenarios. It is evident that the ESV of Sichuan Province in 2025 increases in all four development scenarios compared to 2020. The EP scenario exhibits the highest increase in ESV, with a rise of 2525.50×10^8 yuan. This is followed by the ND scenario, the DP scenario, and the CP scenario, with ESV increases of 2254.02×10^8 yuan, 1940.60×10^8 yuan, and 788.46×10^8 yuan, respectively.

Among the four scenarios, the EP scenario has the highest total ESV, reaching $50{,}903.37 \times 10^8$ yuan, while the ND and DP scenarios have the second highest total ESVs, reaching $50{,}631.90 \times 10^8$ yuan and $50{,}318.47 \times 10^8$ yuan, respectively. The ND scenario continues the current development trend without imposing additional limitations and constraints. The CP scenario focuses on conserving cropland to maintain its quantity and quality, ensuring the growth of crops and food production. The EP scenario maximizes greening, enhances soil and water conservation and disaster resistance, and optimizes living environments. The DP scenario effectively addresses the coordinated development of cropland and ecological protection, positively contributing to the coexistence of humans and nature. In all four scenarios, forests, grasslands, croplands, and water are important components of the ESV, accounting for more than 98%. Forests make the most significant contribution, exceeding 71% in all four scenarios.

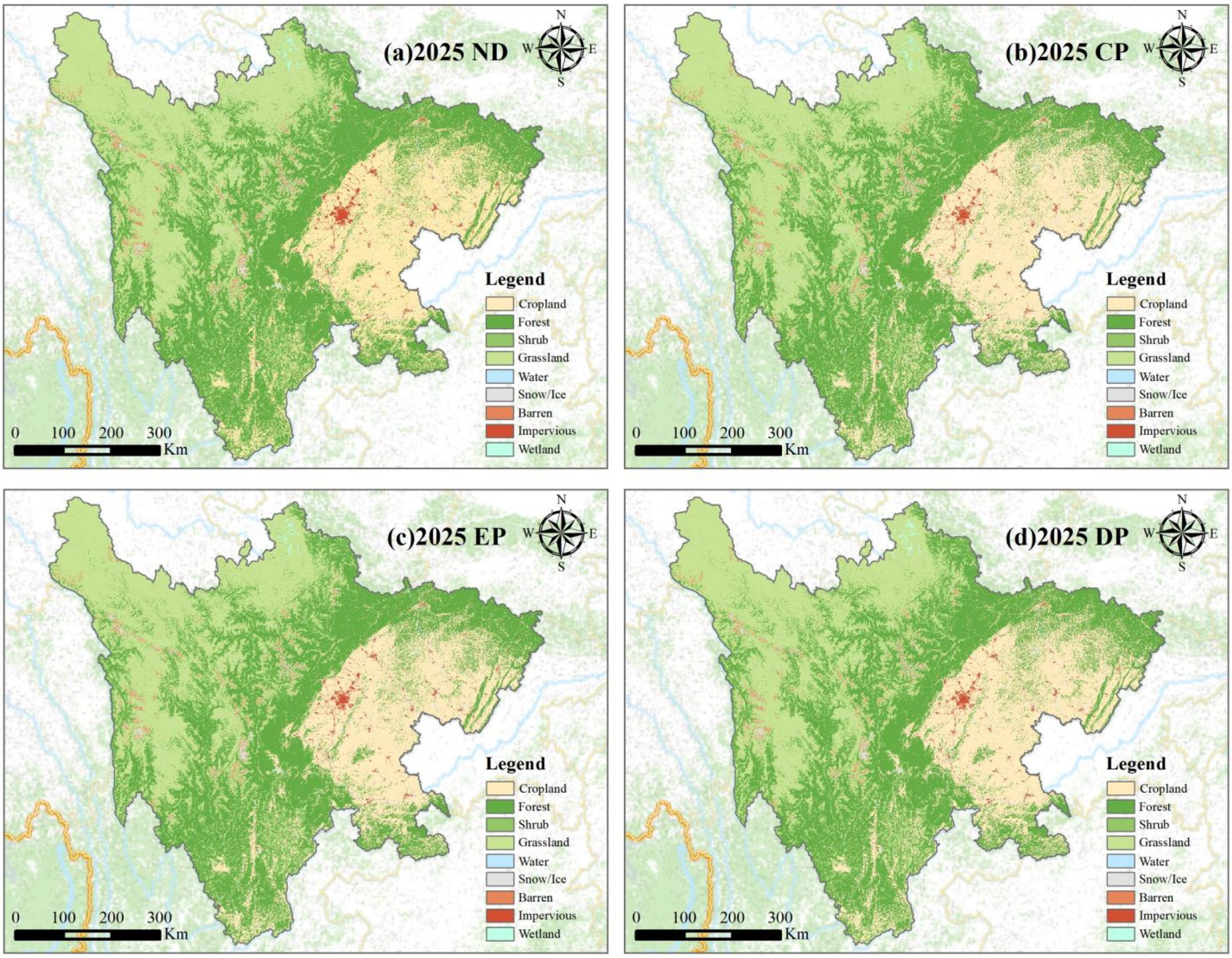

Figure 11. The spatialization results of LC based on the GeoSOS-FLUS model under the NG, CP, EP and DP scenarios in 2025.

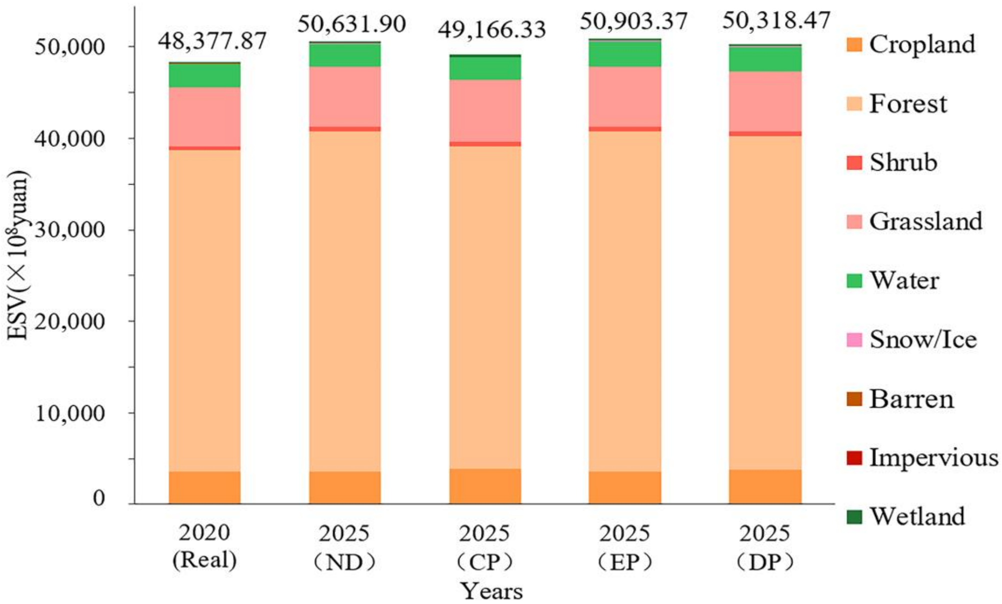

Figure 12. Total values and compositions of ESVs under the NG, CP, EP, and DP scenarios in 2025.

5. Discussion

5.1. Spatiotemporal Evolutionary Patterns of ESV and LC

The world is currently experiencing a rapid population growth, a scarcity of natural resources, and ecological degradation, leading to an increased focus on the need for coordinated development between ecosystems and the economy [20]. Regional LC change is mainly driven by economic development and human activities, which has resulted in land degradation and the reduction of ESs due to the lack of effective measures for harmonious development [42]. Therefore, it is necessary to establish effective ecological management, restoration, and protection mechanisms to optimize LC patterns and maintain ESs [69].

The implementation of major ecological protection and restoration policies in Sichuan Province has had a positive impact on changes in ESV and LC patterns. From 2000 to 2020, there has been a significant increase of 9748 km^2 in the forest area of Sichuan Province, primarily due to the conversion of cropland and grassland. Additionally, the area of water and shrubs have also experienced growth, with increases of 488 km^2 (18.14%) and 32 km^2 (0.78%), respectively. These expansions in ecosystem areas have contributed to the conservation of biodiversity, which is closely linked to the ecological protection and restoration projects implemented. However, it is important to note that there was a substantial increase of 2537 km^2 in impervious areas, which has undoubtedly led to a significant decline in the provision of ESs in the region.

Sichuan, being a large province in terms of its economy, population, and resources, holds a unique and significant position in the national development landscape, particularly in the implementation of the western development strategy [70]. As socio-economic development progresses, urbanization, industrial growth, and various other activities have led to the gradual deterioration of ESs in certain areas with high ESVs. The expansion of areas with zero ESV and degraded grasslands is a concerning trend that requires attention to prevent the further loss of ESV. However, overall, the implementation of major protection and restoration projects has transformed ecosystems with lower unit values (e.g., barren areas, croplands, grasslands) into ecosystems with higher unit values (e.g., water areas, forests, wetlands), contributing to the overall increasing trend of ESV. The overall ESV significantly increased from 35,294.55 $\times 10^8$ yuan to 48,377.87 $\times 10^8$ yuan, representing a cumulative increase of 13,083.32 $\times 10^8$ yuan (Figure 6).

During the implementation of major ecological protection and restoration projects and urban development, noticeable agglomeration effects and imbalances have also emerged. The changes in the barycenter of ESVs were analyzed using the standard deviation ellipse method, revealing that the barycenter was located in northeast of Ya'an City and generally moved towards the northeast during the study period.

5.2. Suitability of Multi-Scenario Simulation Results

Sichuan Province, known for its vast farmland and rich ecological resources, recognizes the significance of protecting cropland and ecosystems to achieve sustainable development. The local government has implemented various measures to safeguard cropland and promote ecological protection alongside economic growth. These include enacting legislation to protect cropland, enhancing the monitoring and evaluation of cropland quality, and strictly addressing illegal encroachments on cropland [66,71]. Additionally, efforts are being made to promote ecological engineering protection and restoration, develop ecological compensation mechanisms, and strengthen the establishment of nature reserves [72]. The four future development scenarios presented in this study align closely with existing policies. Preserving cropland is fundamental to ensuring food security and sustainable agriculture, while ecological conservation involves safeguarding natural ecosystems, preserving biodiversity, and enhancing soil and water conservation.

The validation and uncertainty analysis of the model chain is essential. Due to the infinite number of demands for each type of land in the potential future, predicting future scenarios with a relatively high degree of accuracy is unrealistic. It is challenging to consider all the factors that will influence the future socio-economy. Therefore, the optimal approach is to analyze the distribution of LCs under various development scenarios to explore potential directions for future land patterns, as originally intended. The LC simulation results in this study obtained from the GeoSOS-FLUS model demonstrated a high level of credibility, as evidenced by the kappa coefficient and overall accuracy reaching 0.91 and 94% on average, which surpass existing simulation results of the model [48,73]. The FOM value ranged around 2.67% on average, which is near the standard level for such simulations [20]. In addition, Xie et al. [8] assessed the total ESV in Sichuan Province in 2010 to be around 35,565 $\times$ 10^8 yuan by the same methodology, showing a high agreement of about 93% with the results of this study. Thesevalidates the reasonableness of the study's scenarios and the reliability of the simulation results. Therefore, the future ESV assessment method presented here, based on reasonable scenarios and LC shows potential as a crucial method for long-term policy optimization and the integrated management in the region.

5.3. ESV Evolution Driven by Policy Context

ESs are considered to be valuable contributions from natural ecosystems to humans, and a higher ESV indicates a greater ecosystem contribution [74]. Changes in ESV are closely linked to the development and implementation of real-time policies. Sichuan Province has implemented numerous policies and measures, including the Regulations on Natural Forest Protection in 1999, the Third Phase Project Plan for the Construction of the Protection Forest System in the Yangtze River Basin (2011–2020) in 2011, and the 2017 Sichuan Province's 13th Five-Year Plan for Ecological Protection and Construction [75]. Policies such as the Natural Forest Resource Conservation Project from 2000 to 2020 have played a positive role in guiding the growth of ESV. For instance, the project of returning farmland to forests and grasslands reduces the farming and grazing activities on cropland unsuitable for cultivation and grassland, thus helping to maintain ecological balance and biodiversity. The natural forest resources protection project contributes to the preservation of forest ecosystems and the maintenance of ecological service functions like water conservation, soil retention, climate regulation, and the improvement of air and environmental qualities. The construction project of the protection of forest systems plays a crucial role in soil and water conservation, flood prevention, disaster mitigation, and safeguarding farmlands and cities. From 2000 to 2020, the forest areas increased by a cumulative 9748 km^2, contributing to an increment of 9930.43 $\times$ 10^8 yuan in ESV, with the most important source of growth.

ESV results play a crucial role in making decisions and recommendations for quality development [76]. Figures 9 and 10 indicate that there is spatial clustering and a developmental imbalance in ESVs across the cities in the study area. While an increase in ESV contributes to economic growth to some extent, it does not necessarily guarantee sustained regional economic growth [77]. The rapid growth of impervious areas may boost regional GDP initially, but it can potentially undermine the overall ESV. To address the contradictions and problems arising from the imbalance between human and natural development, the Chinese government introduced a series of natural resource protection laws in 2020, including the new Land Management Law and Forest Law. These laws aim to protect environmentally sensitive land and ensure that urban planning and development are in harmony with ecological protection through legal means [78]. Local governments and policy-makers should tailor their approaches to the specific conditions of their cities. The pattern of ESV aggregation in each city has remained consistent and unchanged over the 20-year period, revealing clear high and low aggregation areas. This highlights the need to prioritize equalization during the declaration, planning, and implementation of major ecological protection and restoration projects. While the rapid economic development of each city may lead to a decline in ESV to some extent, it is crucial that we find a balance that considers both economic and ecological benefits, ensuring regional optimization. In cities with high coordination, continuous dynamic coordination should be maintained, and future development plans should be optimized. Conflict cities like Chengdu and Deyang, which have high levels of economic development but low ESVs, should focus on strengthening the construction of ecological civilizations. Conflict cities with lower levels of economic development but higher ESVs, such as Ganzi and Ngawa, should strive to improve their economic development while also stabilizing their ecological resources. At the national and provincial levels, attention should be given to these issues, and certain policy preferences should be provided. This will ultimately achieve a virtuous cycle and a win-win situation.

5.4. Limitations and Future Work

We have made efforts to improve the framework and rationalization of this study, but there are still limitations that need to be addressed. Firstly, different methods for ESV assessment have their own advantages and disadvantages [5,19]. While the method used in this study is simple and easy to implement, it is important to note that the assessment of an equivalent ESV is somewhat subjective. For example, the ESs such as waste treatment and biological control were not considered in the adopted method. Secondly, the study only collected five periods of LC data, which is insufficient to fully capture ecosystem conversion and detailed changes in ESVs under major ecological protection and restoration projects. To obtain more accurate conclusions, future studies should aim for higher precision data with shorter time intervals [79]. Additionally, when using ARIMA to predict the standard unit equivalent factor value in 2025, it is important to acknowledge that uncertainties still exist. Events such as new epidemics and natural disasters cannot be predicted and may impact changes in the standard unit equivalent factor value. Lastly, the willingness to switch between ecosystems is influenced by national policies and economic development, which can alter an ecosystem's structure and significantly impact ESVs. Although the methodology of this study can serve as a decision-making tool to forecast ESV and LC development trends, it deserves more thought. Looking ahead, it is important to consider utilizing annual national land-use surveys' data for ecosystem classification in order to enhance the accuracy and reliability of decision support. This survey data is more accurate and reliable compared to LC data obtained from low-resolution remote sensing images, and can serve as a solid foundation for ecological evaluation and management [80]. In addition, the further refinement and enrichment of the equivalence factor table through its delineation into relatively specific subcategories is necessary, such as including watered land as a sub-item of cropland ecosystems, and exploring and clarifying the equivalence factors of the cultural service and support service functions of impervious land areas.

6. Conclusions

In this study, considering the implementation of major ecological protection and restoration projects as well as the spatiotemporal variability of ESs, the spatiotemporal dynamic equivalent factor method was utilized to accurately assess the ESVs in Sichuan Province from 2000 to 2020. This study also systematically revealed the LC and ESV change patterns and processes of change in the spatiotemporal sequence of economic and environmental harmonization across cities. Finally, the coupled Markov chain and GeoSOS-FLUS models predicted the pattern of the LC and ESV patterns under four scenarios in 2025. The main findings are as follows:

(1) From 2000 to 2020, there was a consistent increase in the area of forests and impervious land, with forest cover expanding by 9748 km^2. The most frequent transitions were observed between croplands, forests, and grasslands.

(2) The overall ESV remained relatively stable and exhibited a positive trend, with forests playing a significant role in this increase. The barycenter for ESV was found to be in the northeastern part of Ya'an, and it has been gradually shifting northeast since 2000. The ESV associated with the soil and water conservation function demonstrated remarkable performance, with a cumulative increase of 75% compared to that of 2000.

(3) The ESV aggregation pattern of each city has remained unchanged, with Ganzi being the only city with high aggregation. The degradation and imbalanced development in Zigong and Neijiang are constraining the improvement of the overall ESV. Overall, there are more conflict cities than coordination cities between economic development

and the ecological environment. High conflict cities are concentrated in Ganzi, Ngawa, Liangshan, Yan, Bazhong, and Guangdong. Chengdu and its surrounding cities have gradually transitioned from coordination cities to conflict cities. The coordination in Panzhihua and Bazhong shows a continuous trend of improvement.

(4) Our simulation results align closely with the actual LC in 2020. Under all four development scenarios, the ESV of Sichuan Province in 2025 has increased, with the highest total ESV being that under the EP scenario that will reach 50,903.37 $\times 10^8$ yuan.

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Appendix A

Table A1. Equivalents of ESVs supplied per unit area of each ecosystem in Sichuan.

Ecosystem Services		Supply Service			Adjustment Service				Support Service			Cultural Service
		Food Production	Production of Raw Materials	Water Resources' Supply	Gas Regulation	Climate Regulation	Purity of the Environment	Hydrological Regulation	Soil Conservation	Maintenance of Nutrient Cycling	Biodiversity	Aesthetic Landscape
2000	Cropland	1.86	0.46	−1.73	1.50	0.78	0.23	2.04	1.56	0.26	0.29	0.13
	Forest	0.51	1.16	0.52	3.81	11.40	3.39	7.28	7.14	0.35	4.23	1.86
	Shrub	0.33	0.75	0.34	2.47	7.42	2.25	5.14	4.64	0.23	2.75	1.21
	Grassland	0.18	0.25	0.12	0.89	2.35	0.77	1.50	1.67	0.09	0.98	0.44
	Water	1.40	0.40	12.73	1.35	4.02	9.74	157.00	2.51	0.12	4.47	3.32
	Snow/Ice	0.00	0.00	3.32	0.32	0.95	0.28	10.95	0.00	0.00	0.02	0.16
	Barren	0.00	0.00	0.00	0.04	0.00	0.18	0.05	0.05	0.00	0.04	0.02
	Impervious	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Wetland	0.89	0.88	3.98	3.33	6.32	6.32	37.21	6.23	0.32	13.81	8.30
2005	Cropland	1.87	0.46	−1.73	1.50	0.79	0.23	2.03	1.43	0.26	0.29	0.13
	Forest	0.51	1.16	0.52	3.81	11.43	3.39	7.26	6.55	0.35	4.24	1.86
	Shrub	0.33	0.76	0.34	2.48	7.44	2.25	5.13	4.25	0.23	2.76	1.21
	Grassland	0.18	0.25	0.12	0.90	2.36	0.77	1.50	1.53	0.09	0.98	0.44
	Water	1.41	0.40	12.70	1.35	4.03	9.76	156.58	2.30	0.12	4.48	3.32
	Snow/Ice	0.00	0.00	3.31	0.32	0.95	0.28	10.92	0.00	0.00	0.02	0.16
	Barren	0.00	0.00	0.00	0.04	0.00	0.18	0.05	0.05	0.00	0.04	0.02
	Impervious	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Wetland	0.90	0.88	3.97	3.34	6.33	6.33	37.11	5.71	0.32	13.83	8.31
2010	Cropland	1.86	0.46	−1.62	1.49	0.78	0.23	1.91	1.36	0.26	0.29	0.13
	Forest	0.51	1.15	0.49	3.80	11.37	3.38	6.80	6.24	0.35	4.22	1.85
	Shrub	0.33	0.75	0.32	2.47	7.40	2.24	4.81	4.05	0.23	2.75	1.21
	Grassland	0.17	0.24	0.11	0.89	2.34	0.77	1.41	1.46	0.09	0.98	0.44
	Water	1.40	0.40	11.89	1.35	4.01	9.71	146.69	2.19	0.12	4.46	3.31
	Snow/Ice	0.00	0.00	3.10	0.31	0.94	0.28	10.23	0.00	0.00	0.02	0.16
	Barren	0.00	0.00	0.00	0.03	0.00	0.17	0.04	0.05	0.00	0.03	0.02
	Impervious	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Wetland	0.89	0.87	3.72	3.32	6.30	6.30	34.76	5.44	0.31	13.77	8.28
2015	Cropland	1.81	0.45	−1.69	1.45	0.76	0.22	1.99	1.60	0.25	0.28	0.12
	Forest	0.49	1.12	0.51	3.69	11.06	3.29	7.11	7.32	0.34	4.10	1.80
	Shrub	0.32	0.73	0.33	2.40	7.20	2.18	5.02	4.75	0.22	2.67	1.17
	Grassland	0.17	0.24	0.12	0.87	2.28	0.75	1.47	1.71	0.09	0.95	0.43
	Water	1.36	0.39	12.43	1.31	3.90	9.45	153.30	2.57	0.12	4.34	3.22
	Snow/Ice	0.00	0.00	3.24	0.31	0.92	0.27	10.69	0.00	0.00	0.02	0.15
	Barren	0.00	0.00	0.00	0.03	0.00	0.17	0.04	0.06	0.00	0.03	0.02
	Impervious	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Wetland	0.87	0.85	3.88	3.23	6.13	6.13	36.33	6.38	0.31	13.40	8.05
2020	Cropland	1.83	0.45	−1.72	1.47	0.77	0.22	2.03	2.09	0.26	0.28	0.12
	Forest	0.50	1.13	0.52	3.73	11.17	3.32	7.24	9.60	0.34	4.14	1.82
	Shrub	0.33	0.74	0.34	2.42	7.27	2.20	5.12	6.23	0.22	2.70	1.19
	Grassland	0.17	0.24	0.12	0.88	2.30	0.76	1.50	2.25	0.09	0.96	0.43
	Water	1.37	0.40	12.67	1.32	3.94	9.54	156.25	3.37	0.12	4.38	3.25
	Snow/Ice	0.00	0.00	3.30	0.31	0.93	0.27	10.90	0.00	0.00	0.02	0.15
	Barren	0.00	0.00	0.00	0.03	0.00	0.17	0.05	0.07	0.00	0.03	0.02
	Impervious	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Wetland	0.88	0.86	3.96	3.27	6.19	6.19	37.03	8.37	0.31	13.53	8.13

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