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Characterizing Production–Living–Ecological Space Evolution and Its Driving Factors: A Case Study of the Chaohu Lake Basin in China from 2000 to 2020

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Abstract: The division of the territorial space functional area is the primary method to study the rational exploitation and use of land space. The research on the Production–Living–Ecological Space (PLES) change and its motivating factors has major implications for managing and optimizing spatial planning and may open up a new research direction for inquiries into environmental change on a global scale. In this study, the transfer matrix and landscape pattern index methods were used to analyze the temporal changes as well as the evolution features of the landscape pattern of the PLES in the Chaohu Lake Basin from 2000 to 2020. Using principal component analysis and grey correlation analysis, the primary driving indicators of the spatial changes of the PLES in the Chaohu Lake Basin and the degree of the influence of various driving factors on various spatial types were determined. The study concluded with a few findings. First, from the standpoint of landscape structure, the Chaohu Lake Basin's agricultural production space (APS) makes up more than 60% of the total area, and it and urban living space (ULS) are the two most visible spatial categories. Second, the pattern of the landscape demonstrates that the area used for agricultural production holds a significant advantage within the overall structure of the landscape. Although there is less connectedness between different landscape types, less landscape dominance, and more landscape fragmentation, the structure of different landscape types tends to be more varied. Third, the findings of the driving analysis demonstrate that the natural climate, population structure of agricultural development, and industrial structure of economic development are the three driving indicators of the change of the PLES. Finally, in order to promote the formation of a territorial space development pattern with intensive and efficient production space, appropriate living space, and beautiful ecological space, it is proposed to carry out land regulation according to natural factors, economic development, national policies, and other actual conditions.

Keywords: production–living–ecological space; spatiotemporal evolution; driving mechanism; Chaohu Lake Basin; principal component analysis; grey relational analysis

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1. Introduction

Globally, industrialization and urbanization have caused a series of social and environmental problems, and the contradiction between urban, agricultural, and ecological spaces is particularly prominent in developing countries. Numerous studies have shown [1,2] that the unbalanced pattern of urban, agricultural, and ecological spaces reflects the impact of human activities on the natural environment, causing social and ecological problems such as natural disasters, energy shortages, and ecological degradation. The International Geosphere-Biosphere Program (IGBP) and the Human Dimensions in Global Environmental Change Program (IHDP), among others, have proposed the study of land use change patterns and the analysis of driving forces as core research directions to reduce the negative impacts of land use change on nature and society [3].

China has experienced rapid economic growth and urban expansion since its reform and opening up in 1978, and since then land use conflicts have become increasingly intense, leading to a series of problems such as the continuous increase in urban construction space, ecological degradation of forest land and water resources space, and environmental pollution [4–6]. China's land development has been changing from a purely production space-oriented model to a production–living–ecological space (PLES) coordinated development model [7]. In response, building a spatial planning system of "intensive and efficient production space, livable and moderate living space, and beautiful ecological space", i.e., production, living, and ecological space, has become the core content of the Chinese government to strengthen spatial control and sustainable development. The land is the spatial carrier of ecological civilization construction and the material basis of spatial planning. It has three major functions: production, living, and ecology, among which ecological function is the basis and the premise of production and living [8]. The three are unified and indivisible. The PLES is a type of land space classified based on the main functions of land, which is the basic paradigm of the macro-scale cognition of land space and the functional attributes of land space. Although this concept is seldom used internationally, there are many similarities between foreign research on urban functional space and multifunctional land use and Chinese research on the classification of the PLES [9–11], i.e., the exploration from the perspective of spatial planning and management can better balance and coordinate regional production, ecological, and living spaces. Previous studies on PLES have mainly focused on the construction of theoretical frameworks [12], functional space identification and classification [13–15], and evaluation and optimization [16–18], focusing on spatial patterns but neglecting landscape functions and processes. Further research on the driving forces behind the evolution of functional spatial form and structure will help to address the challenges related to regional spatial imbalance and ecosystem degradation. Therefore, in this context, it is necessary to clarify the relationship between the spatial evolution and drivers of the PLES.

In addition, some studies have shown that, with the development of social and economic development and urbanization, the number of population surges, urban land and rural settlements continue to expand, the degree of land use change intensifies, leading to uncontrolled spatial development, regional disorderly competition, tightening resource constraints, and serious ecological and environmental damage, which are consistent with the performance of the urbanization process and are the most direct influencing factor for the more prominent spatial contradictions of various land uses [19,20]. The gradual disorder of the relationship between human production, living, and ecological spaces has accelerated the evolution of land space patterns. In essence, a landscape pattern is mainly composed of land use, shape, size, and the spatial configuration of land cover types [21]. Landscape pattern changes affect the structure and function of ecosystems by affecting the types, areas, and spatial distribution of various land uses [22]. Studies have shown [23] that economic development, natural factors, and intensity of human activities affect the change of landscape patterns to some extent, and in areas with intense human activities, the natural landscape will undergo great changes. The analysis of landscape pattern index changes can promote the sustainable development of watersheds by linking the spatial characteristics and temporal processes of regional landscapes, further exploring the potential patterns of human activity intensity and landscape structure evolution.

As the birthplace of human civilization, the lake basin has traditionally had high population densities and intensive land usage, serving an irreplaceable role in the development of human societies. In recent years, the role between land use change and watershed ecology has become a hot topic of research for domestic and foreign scholars [24,25]. The concept of "lake basin" is a way to analyze the lake ecosystem. It is based on the ecological environment index of the lake and looks at the interaction between the lake and the ecological environment of the whole basin. The lake basin, as a unique geographical natural unit, not only emphasizes the role of ecological environment in the whole basin, but also reflects the close relationship between the lake and the whole basin. The shrinking of lake water bodies not only threatens the regional water ecological security, but also seriously affects the developing sustainable social economy. Existing studies at the watershed scale have mainly focused on the description and summary of the pattern and evolution of the PLES and the interaction with ecological and environmental effects [13,26–28], but less research has been conducted on the quantitative factors and driving mechanisms of the evolution of the production and living ecological space patterns. Therefore, it is necessary to analyze the three spatial changes and their internal drivers, as well as the changes in landscape patterns, to better understand human activities and optimize land spatial change patterns; improve the efficiency of land spatial changes; balance regional production, living, and ecological spaces; and achieve the goal of sustainable development.

Chaohu Lake Basin is a typical lake basin located in the center of the Wanjiang Urban Belt, which is a new industrial demonstration area. Urbanization and industrialization are occurring rapidly there, especially the fast-paced growth of construction land in the city of Hefei. Under the severe interference of human activities, the conflict between ecological pressure and economic development has become increasingly prominent. Compared with the research results of the Yangtze River basin and the Yellow River basin, less attention has been paid to the Chaohu Lake Basin, with current studies mainly focusing on land use change [29,30], water environmental protection and management [31,32], and ecological and environmental quality optimization [33,34]. Some studies have shown [35] that a series of ecological problems such as landscape fragmentation, ecological degradation, and water quality pollution have emerged in the Chaohu Lake Basin, mainly due to the imbalance within the production, living, and ecological spaces [36]. However, few existing research results have explored the driving mechanisms of the PLES changes from a territorial spatial perspective; knowing the influencing factors of the PLES changes can effectively solve the problem of spatial imbalance. Therefore, it is urgent to analyze the process of the PLES change in the Chaohu basin and quantify its driving factors.

The objectives of this research were (1) to investigate the changes of PLES in the Chaohu Lake Basin; (2) to study the changes in PLES landscape patterns in the Chaohu Lake Basin; and (3) to explore the influence of regional natural climatic factors and socioeconomic factors on the change process of the PLES. To this end, we established a landscape dataset, obtained the evolutionary characteristics of production–life–ecology using the transfer matrix and landscape pattern index methods, and explored the driving mechanisms through a combination of principal component analysis and gray correlation analysis. This research used the Chaohu Lake watershed to conduct an empirical study to explore the development status of the lake watershed and the development direction of territorial spatial planning and management. The result can provide scientific insights for the protection and management of the Chaohu Lake watershed and better promote the integrated protection and restoration of forests, fields, lakes, and grasses. It can also be used as a reference for ecological function zoning, which is applicable for various natural watersheds around the world.

2. Overview of the Research Area and Research Methods

2.1. Study Area

Chaohu Lake is one of the five major freshwater lakes in China in the middle and lower reaches of the Yangtze River. Considering the availability of data, the counties involved in the Chaohu Lake Basin were included in the research area, covering 11 districts and counties in 4 cities (Hefei, Wuhu, Lu'an, and Ma'anshan), with a total area of about 19,600 km^2 (Figure 1). It belongs to the water system on the north bank of the middle and lower reaches of the Yangtze River. The basin is bounded by the Jianghuai watershed in the northwest, the Yangtze River in the south, Dabie Mountain in the west, and the Chuhe River basin in the northeast. The terrain lowers in altitude from west to east. The upper reaches of the Hangbu River are mountainous areas with an altitude of about 1500 m; the northeast is hills and shallow mountainous areas, and the plain water network areas are along the river and lake. The research area belongs to the northern subtropical humid monsoon climate, with an average annual temperature of 16 °C and a relative humidity of 76%. The climate is mild and humid with four distinct seasons, moderate precipitation, abundant heat, and a long frost-free period. Chaohu Lake Basin, as the center of the Wanjiang urban belt of the new industrial demonstration zone, has obvious advantages in location conditions and development policies. Among them, the urbanization rate of Hefei City in 2018 reached 54.7%, the GDP was 782.291 billion yuan, and the secondary and tertiary industries accounted for 46.2% and 50.3% of the total. In recent years, due to the excessive plundering of fishery resources, human activities (such as reclamation of lakes), and environmental pressures caused by population growth, the ecological environment of Chaohu Lake and the Chaohu Lake Basin has suffered great damage.

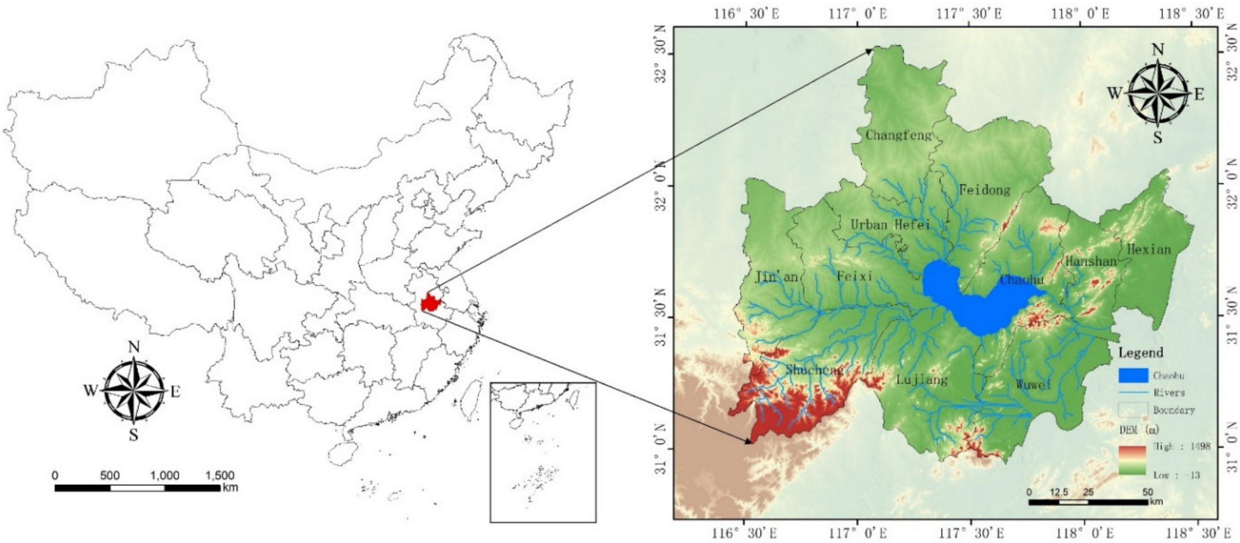

Figure 1. Geographical map of the study area.

2.2. Data Source and Preprocessing

The research uses the land use data from the Chinese Academy of Sciences Resource and Environment Science Data Center, and the overall accuracy of the data exceeds 80%. The data divide the land use types of the Chaohu Lake Basin into paddy fields, dry land, rural settlements, forest land, shrub forest, sparse forest land, other forest land, (high, medium, low) coverage grassland, bare land, bare rock texture, rivers, lakes, reservoirs, ponds, beach, urban land, other construction land, and another 18 types of landscapes.

Combining the natural environment and social conditions of the Chaohu Lake Basin and referring to the existing research progress [35,37,38], 13 indicators were selected from natural, social, economic, population, and other aspects. These include namely annual precipitation (X1), annual average temperature (X2), DEM (X3), Slope (X4), GDP (X5), GDP per capita (X6), primary industry value (X7), secondary industry value (X8), tertiary industry value (X9), urban population (X10), total population (X11), urbanization rate (X12), and the gross output value of agriculture, forestry, animal husbandry, and fishery (X13). This study used ArcGIS 10.2 to interpolate the meteorological drivers (precipitation and temperature) in the PLES change of the lake basin, and then performed zonal statistics for elevation, slope, precipitation, and temperature to satisfy the driver analysis process. In order to facilitate calculation and analysis, all spatial data were resampled in ArcGIS to unify the spatial resolution to 30 m. The coordinate system is WGS_1984_UTM_zone_50N. The relevant data sources involved in the study are described in Table 1.

Table 1. Data source.

Data Type	Data Name	Native Resolution	Year	Data Source	Note
Basic data	Chaohu Lake Basin Boundary	-	2020	Refer to previous literature	-
	Land use data	30 m	2000 2010 2020	Resource and Environmental Science Data Center, Chinese Academy of Sciences, http://www.resdc.cn (accessed on 5 December 2021)	Cropped with Chao Lake Basin vector border
Natural Factors	Annual precipitation (X1)	-	2000 2010 2020	Data Summary of China's Surface Climate Data (V3.0), https://data.cma.cn/ (accessed on 5 December 2021)	Meteorological stations were collected and 30 m spatial raster data were Generated using IDW interpolation in GIS
	Average temperature (X2)				
	DEM (X3)	30 m	-	Geospatial Data Cloud http://www.gscloud.cn/ (accessed on 5 December 2021)	Cropped with Chao Lake Basin vector border
	Slope (X4)	30 m	-	-	Slope Analysis in GIS Based on DEM Data
Socioeconomic Data	GDP (X5), GDP per capita (X6), Primary industry value (X7), Secondary industry value (X8), Tertiary industry value (X9), urban population (X10), total population (X11), urbanization rate (X12), Gross output value of agriculture, forestry, animal husbandry and fishery (X13)	-	2000 2010 2020	Statistical Yearbook of counties and cities in Chaohu Lake Basin from 2001 to 2021	Due to the lack of some statistical yearbook data in Jin'an District, Lu'an City, the driving factor data discussed in this study did not include Jin'an District.

2.3. Research Methods

Based on the classification data of land use coverage under 30 m and combined with the classification system of territorial space, this paper first constructed the classification system of PLES and divided the territorial space into six categories: Agricultural production space (APS), industrial production space (IPS), urban living space (ULS), rural living space (RLS), green ecological space (GES), and water ecological space (WES). Based on the spatial distribution map of the classification system, the land use transfer matrix and landscape pattern index were analyzed, and the spatial structure and spatiotemporal evolution characteristics of Chaohu Lake Basin were preliminarily recognized. On this basis, 13 natural, social, and economic factors were selected to analyze the mechanism that had driven the change of PLES in Chaohu Lake Basin from 2000 to 2020, using principal component analysis and grey correlation analysis. The overall process is shown in Figure 2.

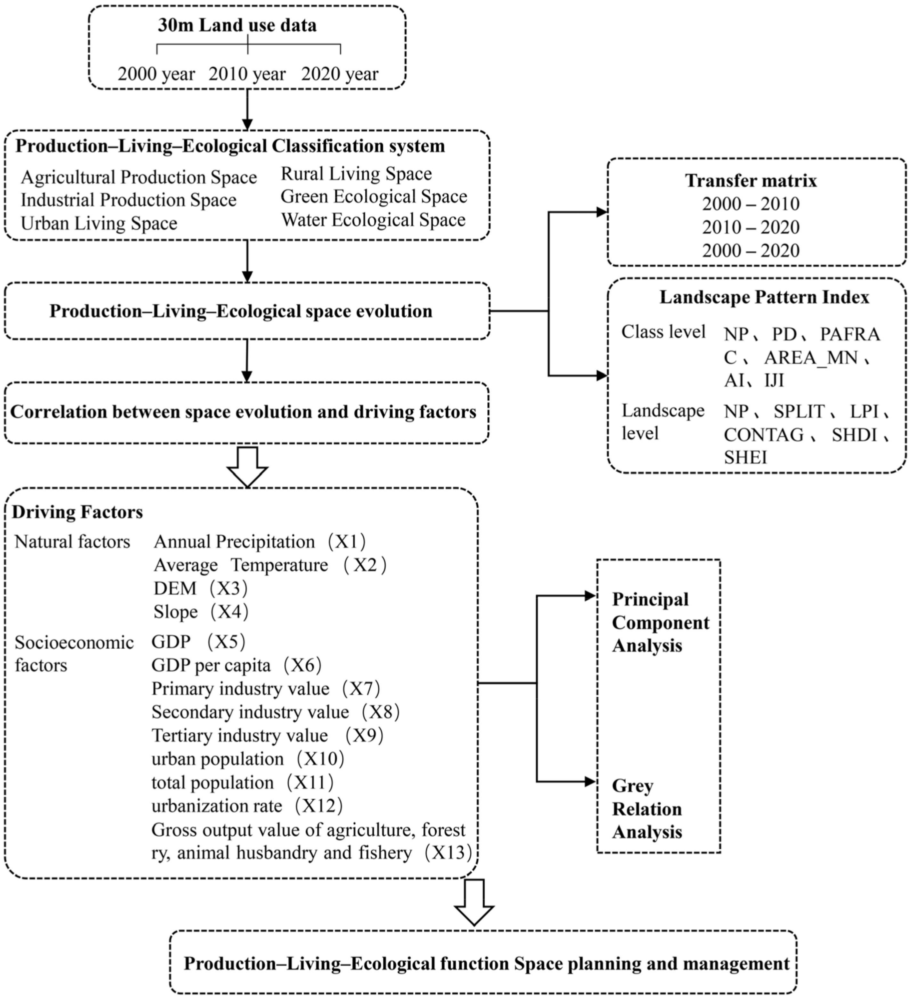

Figure 2. The overall process of the methodology.

2.3.1. Production–Living–Ecological Space Classification Method

Starting from the perspective of the integration of territory resources, this paper refers to the previous research results of PLES functional classification [8,26,27], and establishes a PLES classification system in the Chaohu Lake Basin according to the land use type of the Chaohu Lake Basin (Table 2).

Table 2. The PLES classification method of the Chaohu Lake Basin.

Primary Classification	Secondary Classification	Corresponding Land Use Type
Production space	Agricultural Production Space (APS)	Paddy field, dry land
	Industrial Production Space (IPS)	Other construction land
Living space	Urban Living Space (ULS)	Urban land
	Rural Living Space (RLS)	Rural settlement
Ecological space	Green Ecological Space (GES)	Woodland, shrub forest, sparse woodland, other woodland, (high, medium, low) coverage grassland, bare land, bare rock texture
	Water Ecological Space (WES)	Canals, lakes, reservoirs, ponds, beaches

2.3.2. Transition Matrix

The quantitative analysis of the evolution characteristics of land use in a specific area in a certain period is usually realized by the land use transfer matrix method [39]. In this paper, ArcGIS 10.2 software was used to perform spatial superposition, area tabulation, and summarization of the data of PLES to obtain the area transfer matrix of the PLES type at each stage of the Chaohu Lake Basin. The transfer matrix formula is:

$$S_{mn} = \begin{bmatrix} S_{11}S_{12} & \cdots & S_{1n} \\ S_{21}S_{22} & \cdots & S_{2n} \\ \vdots \quad \vdots & & \vdots \\ S_{m1}S_{m2} & \cdots & S_{mn} \end{bmatrix} \tag{1}$$

In this formula, S_{mn} is the total area of the study area (km^2), and m and n are the land use types at the beginning and end of the study period, respectively.

2.3.3. Selection and Calculation of Landscape Pattern Index

The landscape pattern index is a quantitative research method used to describe landscape change and establish the relationship between landscape patterns and landscape processes. The landscape index is divided into three indices, namely patch, class, and landscape level. In order to fully reveal the changes in the landscape pattern of the Chaohu Lake basin in terms of fragmentation, heterogeneity, and connectivity over the past 20 years, this paper refers to relevant literature [40,41]. A quantitative analysis of landscape pattern characteristics at the patch type and landscape level is proposed and six indicators are selected, including number of patches (NP), patch density (PD), perimeter area fractal dimension (PAFRAC), patch area mean (AREA_MN), aggregation index (AI), and interspersion juxtaposition index (IJI) at the pattern level. In addition, at the landscape level, this paper selects six indicators, including number of patches (NP), splitting index (SPLIT), largest patch index (LPI), contiguity index (CONTAG), Shannon's diversity index (SHDI), and Shannon's evenness index (SHEI). The specific ecological meanings of the relevant indices are explained in Table 3.

Table 3. Description of landscape pattern index.

Level	Landscape Pattern Index	Abbreviation/Unit	Ecological Significance
Class	number of patches	NP/number	Used to describe the heterogeneity of the whole landscape, and its value has a good positive correlation with the fragmentation of the landscape.
	patch density	PD/(per 100 hm^2)	Indicating the degree of fragmentation of a certain type, reflecting the heterogeneity in the unit area of the landscape.
	perimeter area fractal dimension	PAFRAC	To a certain extent, it reflects the interference degree of human activities. When the index value is smaller, that is, it tends to 1, indicating that the shape of the patches in the landscape is relatively simple, and the degree of interference by human activities is small. The greater tending to 2, the more complicated and the higher degree of interference by human activities.
	patch area mean	AREA_MN/hm^2	Indicating the fragmentation degree of the landscape, and the smaller value the more fragmented, which is the key to reflect the heterogeneity of the landscape.
	aggregation index	AI/%	The connectivity between the patches of landscape type, the smaller the value, the more discrete the landscape.
	interspersion juxtaposition index	IJI/%	A small value indicating that the patch type is only adjacent to a few other types; IJI = 100 indicates that the adjacent side lengths between each patch are equal, that is, the adjacent probability between each patch is equal.
Landscape	number of patches	NP/number	Used to describe the heterogeneity of the whole landscape, and its value has a good positive correlation with the fragmentation of the landscape.
	splitting index	SPLIT	The larger the value, the more fragmented the landscape and the scattered distribution.
	largest patch index	LPI/%	Helping to determine the pattern or dominant type of the landscape, etc. Its value determines ecological characteristics such as the abundance of dominant species and internal species in the landscape; the change of its value can reflect the intensity and frequency of disturbance, and the direction and strength of human activities.
	contiguity index	CONTAG/%	Indicates the degree of aggregation or extension of different patch types. A high value indicates that a certain dominant patch type in the landscape is well connected; otherwise, it indicates that the landscape is a dense pattern with multiple elements, and the landscape has a high degree of fragmentation.
	Shannon's diversity index	SHDI	Indicating that the richer the land use types, and the higher the degree of fragmentation, and the greater the information content of its uncertainty.
	Shannon's evenness index	SHEI	When the value is small, the dominance degree is generally high, which can reflect that the landscape is dominated by one or a few dominant patch types; when the value approaches 1, the dominance degree is low, indicating that the landscape has no obvious dominant type and the patch types are uniform distributed.in the landscape.

2.3.4. Principal Component Analysis

The basic idea of principal component analysis is to reduce dimensionality [42]. By eliminating redundant information in the driving factors and retaining most of the original multivariate information, driving factor indices are replaced by fewer index components and the relationship between fewer index components and dependent variables is explored. The method is always used in studying the driving force of land use and is applied to the 13 selected factors using the "dimensionality reduction-factor" module in SPSS Statistics 25.

2.3.5. Grey Relational Analysis

Grey relational analysis [43] is a method used to measure the correlation between factors according to the degree of similarity or dissimilarity of the development trends between factors, and determines the degree of their correlation, which is suitable for the analysis of dynamic processes with less data and difficulties in distinguishing primary and secondary factors [44]. Calculating the correlation degree between the driving factors and the area change of each secondary PLES can help determine the degree of driving effect of the factor. The higher the correlation degree is, the stronger the correlation will be, which means it can effectively avoid the inaccuracy of single factor analysis. In this paper, the mean de-dimensioning method is used—that is, the ratio of the original data of each year to the mean value of the year. At time t = k, the expression of the correlation coefficient between the parent sequence and the characteristic sequence is:

$$\gamma_{0i}(k) = \frac{[\Delta(\min) + \rho\Delta(\max)]}{[\Delta_{0i}(m) + \rho\Delta(\max)]} \tag{2}$$

where $\gamma_{0i}(k)$ is the correlation coefficient between the parent sequence and the characteristic sequence at time k; $\Delta(\min)$ and $\Delta(\max)$ are the minimum absolute difference and the maximum absolute difference at each moment of all the comparison sequences, respectively; $\Delta_{0i}(k)$ is the absolute difference between the parent sequence and the characteristic sequence at time k; and ρ is the resolution coefficient with a value of 0.5. There are a numbers of correlation coefficients between the parent sequence and the characteristic sequence, and the correlation coefficient values need to be averaged to calculate the gray correlation degree. The expression is:

$$\gamma_{0i} = \frac{1}{N}\sum_{k=1}^{n} \gamma_{0i}(k) \tag{3}$$

where γ_{0i} is the degree of correlation between the parent sequence $\{X_0(t)\}$ and the characteristic sequence $\{X_i(t)\}$; and n is the length of the time series.

3. Results

3.1. The Spatiotemporal Evolution Characteristics of the Production–Living–Ecological Space in the Chaohu Lake Basin

3.1.1. Analysis of Structural Changes of Production–Living–Ecological Space

Figures 3 and 4 show that APS is the most dominant landscape type, accounting for more than 60% of the total area and concentrated in the Chaohu Plain area. The Chaohu Plain area is low in elevation and flat, suitable for human production and living activities, with high potential for agricultural production and conducive to the construction of high-quality commodity grain bases and green food bases. During the study period, the amount of change in the area of the PLES Space was APS > ULS > IPS > RLS > WES > GES. The APS shrank the fastest, with the area reducing by 805 km^2 and a growth rate of -40.25 km^2/year, from 13,304.56 km^2 in 2000 to 12,499.55 km^2 in 2020. RLS was mainly concentrated in the Hefei city district, with the Hefei city district as the core spreading outward from the inside, with the area increasing by 479.45 km^2 and a growth rate of 23.97 km^2/year, from 189.34 km^2 in 2000 to 668.80 km^2 in 2020. IPS continued to increase, with increasing by 164.05 km^2, from 23.41 km^2 in 2000 to 187.46 km^2 in 2020; and RLS and WES increased slowly by 140.80 km^2 and 16.94 km^2, respectively. GES was mainly distributed in mountainous and hilly areas. These areas with high altitudes and steep slopes are not conducive to residential and production activities and the proportion of their ecological space area was significantly higher than that of other spaces. The acceleration of urbanization, the transfer of industries, the pursuit of high-quality life by residents, and the gradual transfer of residents to urban economic centers have led to the continuous expansion of ULS, encroaching on large areas of APS. Water resource projects are constantly being built, water resources restoration and protection projects are being carried out, and the watershed area is increasing.

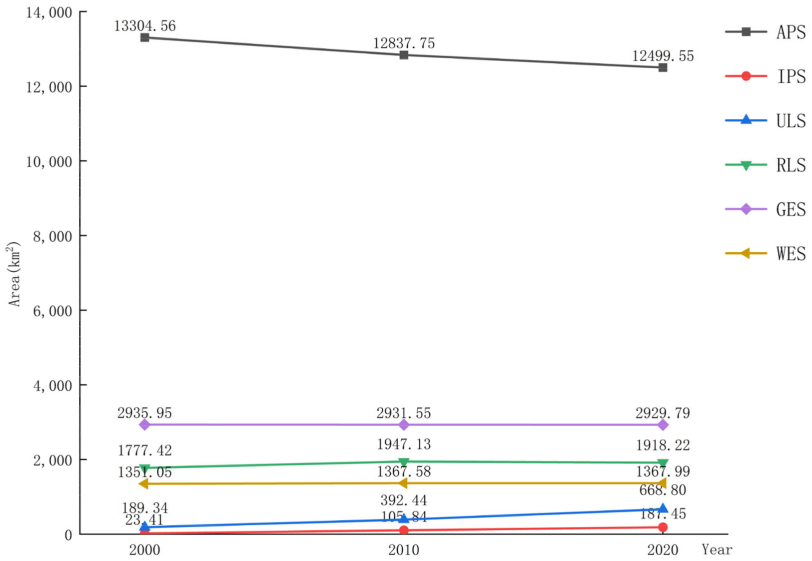

Figure 3. Area change of PLES in the Chaohu Lake Basin from 2000 to 2020.

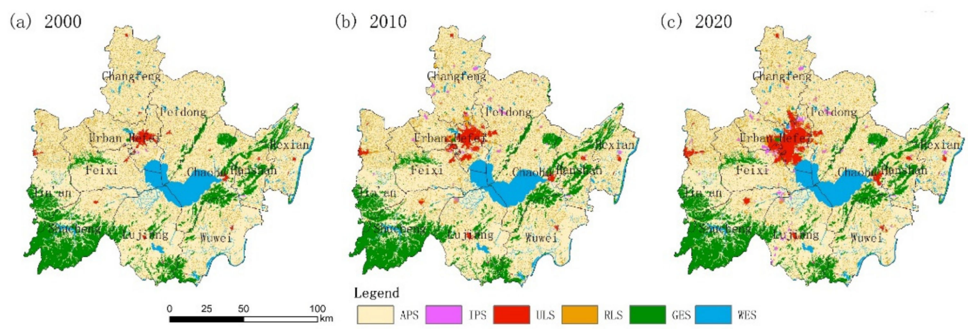

Figure 4. The Pattern of PLES in the Chaohu Lake Basin in 2000 (**a**), 2010 (**b**), 2020 (**c**).

3.1.2. Production–Living–Ecological Space Type Conversion

From the transition matrix from 2000 to 2020 (Figure 5), the area of each type of space has changed to different degrees in each time period, mainly manifested in the interchange of living and production spaces and the transfer of production to ecological space, while the most prominent transfer trend is the transfer of agricultural production to other spatial types, mainly to IPS and living space, decreasing at the rate of 40.25 km^2 per year (2000–2010 and 2010–2020). From 2000 to 2010, living space occupying production space and production space occupying ecological space were the main transfer trends; within this, APS was transformed into ULS, RLS, and IPS, with the transfer areas of 186.77 km^2, 203.23 km^2, and 75.38 km^2, respectively. From 2010 to 2020, the main transfer trend was from production space into living space and from production space into ecological space. The transformation trend of APS was basically the same as that in the previous period. The area of RLS transferred out increased, mainly shifting to ULS and APS, with transferred areas of 73.71 km^2 and 71.62 km^2, respectively. In general, from the transferred-in and transferred-out land types in the Chaohu basin throughout the study period, the transferred-in living space was mainly APS, accounting for 97.96% of the total transferred in, and the transferred-out living space was less, only 11.28% of the total amount of living space transferred in.

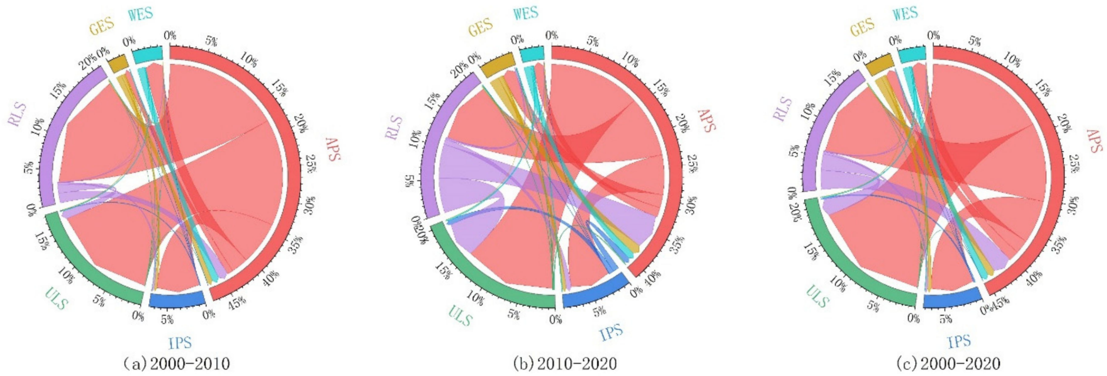

Figure 5. Land use change transition matrix from year in 2000–2010 (**a**), 2010–2020 (**b**), and 2000–2020 (**c**) (unit: km^2).

Figure 6 shows that the evolution of the PLES in the Chaohu Lake basin is characterized by agglomerative changes. The increase of ULS is mainly distributed in the Hefei city district. The contribution of APS is the largest, accounting for 86.24% of the total transfer of ULS, followed by the transfer of RLS, accounting for 11.72%. The increase in IPS is more scattered, mainly in the municipal district, Changfeng County, Feidong County, Feixi County, and Lujiang County, and 87.46% of the increase in area comes from APS. The increase in RLS is mainly distributed around Chaohu Lake, Hefei City, Changfeng County, Feidong County, Feixi County, and Wuwei County, with 98.35% of the increase in area coming from APS. The increased area of WES is mainly distributed around the northwest rivers of Chaohu Lake, and 94.29% of the area increase comes from APS. Overall, the PLES located in the Hefei city district have the most significant changes, and the areas of living space expansion and production space loss are highly overlapping.

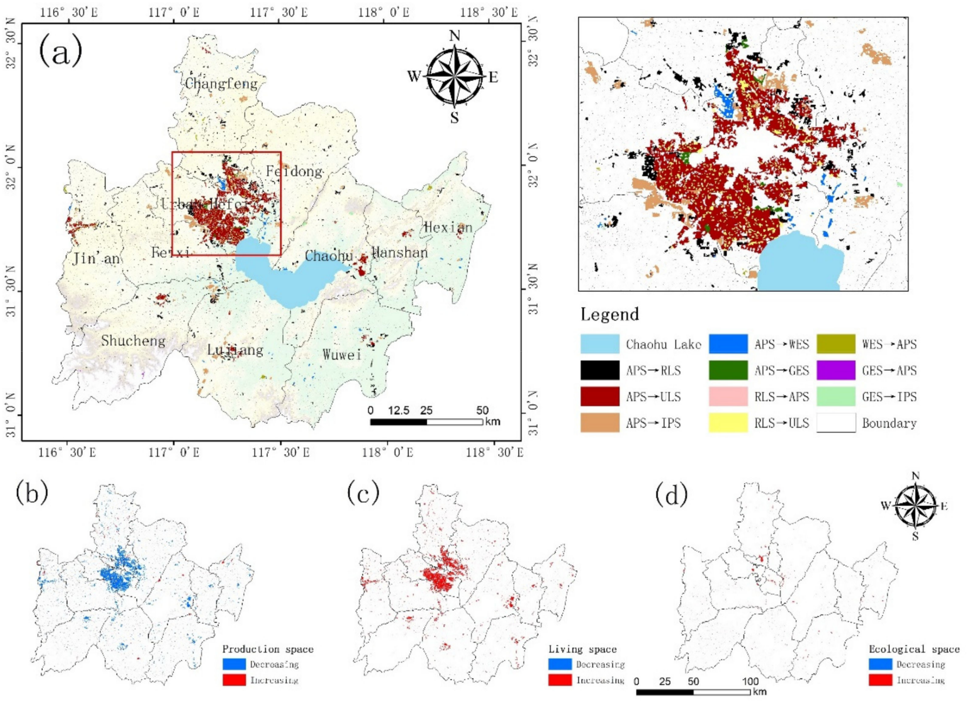

Figure 6. (**a**) shows the secondary space transfer from year 2000 to 2020; (**b**) shows the increase and decrease distribution of production; (**c**) shows the increase and decrease distribution of living; (**d**) shows the increase and decrease distribution of ecological spaces.

3.2. Temporal and Spatial Changes of Landscape Pattern in Chaohu Lake Basin

The landscape pattern indices were calculated using Fragstats 4.2 at the landscape type level and the patch type level for the years 2000, 2010, and 2020. The results are shown in Figures 6 and 7. The landscape type level indices reflect the overall structural characteristics of the landscape. NP, LPI, and CONTAG in Chaohu Lake Basin all show a downward trend from 2000 to 2020; LPI decreased from 67.79% to 61.51%, and CONTAG decreased from 67.45% to 63.23%. This indicates that, as human socioeconomic activities intensify and the intensity of disturbance increases, there is a weakening role of the dominant patch types in Chaohu Lake Basin in landscape control in the form of decreased connectivity of dominant patches, intensified landscape fragmentation, and decreased anti-interference ability of the landscape. SPLIT, SHDI, and SHEI show an upward trend: the SHDI index increased from 1 to 1.14, the landscape types were rich and tended to be diversified, and the landscape dominance decreased; the SHEI was all greater than 0.56 and continued to increase, and the landscape patches were generally distributed more evenly.

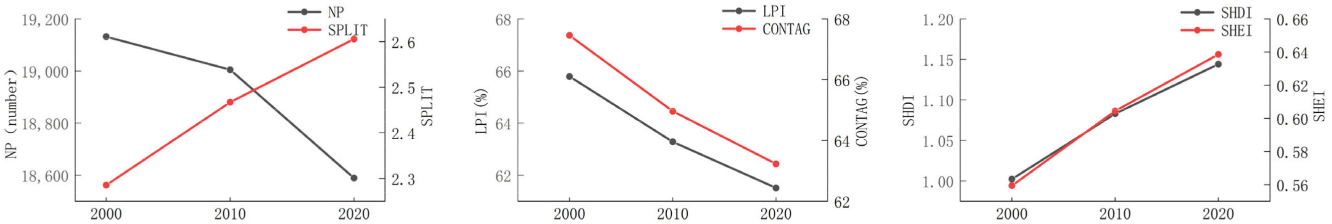

Figure 7. Landscape Level Index of Chaohu Lake Basin in 2000, 2010, and 2020.

The patch type level reflects the respective structural characteristics of different patch types in the landscape (Figure 8). The AI index of ULS increased from 96.87% to 98.75%, while the AI of other spaces changed more moderately. NP, PD, and IJI of APS increased year by year, and AREA_MN, PAFRAC, and AI of APS decreased year by year, indicating that urban construction led to the increase of fragmentation of APS. NP, PD, AREA_MN, and PAFRAC of IPS increased year by year, IJI of IPS increased and then decreased, and IJI increased from 59.72% to 75.11% from 2000 to 2020, indicating that the landscape fragmentation of IPS increased. NP, PD, PAFRAC, and IJI of WES increased and AREA_MN of WES decreased. NP and PD decreased and AREA_MN, PAFRAC, and IJI of GES increased. NP and PD of ULS increased and then decreased, AREA_MN decreased and then increased, PAFRAC increased and then decreased, and IJI increased year by year. NP and PD of RLS decreased, AREA_MN, IJI increased year by year, and PAFRAC decreased and then increased, indicating that human activity disturbance gradually increased. In general, the fragmentation of APS, IPS, WES, and GES increased, and the spatial aggregation of ULS and RLS increased.

3.3. The Driving Force of Temporal and Spatial Evolution of Landscape Pattern in Chaohu Lake Basin

The analysis of changes and landscape patterns of the PLES in the Chaohu Lake basin from 2000 to 2020 considered spatial heterogeneity, fragmentation, and the comprehensive coverage of spatial drivers, making the analysis process of driving mechanisms more comprehensive and objective. Therefore, this study selected principal component analysis and gray correlation analysis to quantitatively explore the main driving indicators and the dominant factors of each spatial type of change in the Chaohu Lake Basin from three aspects: natural factors, economic development, and human activities.

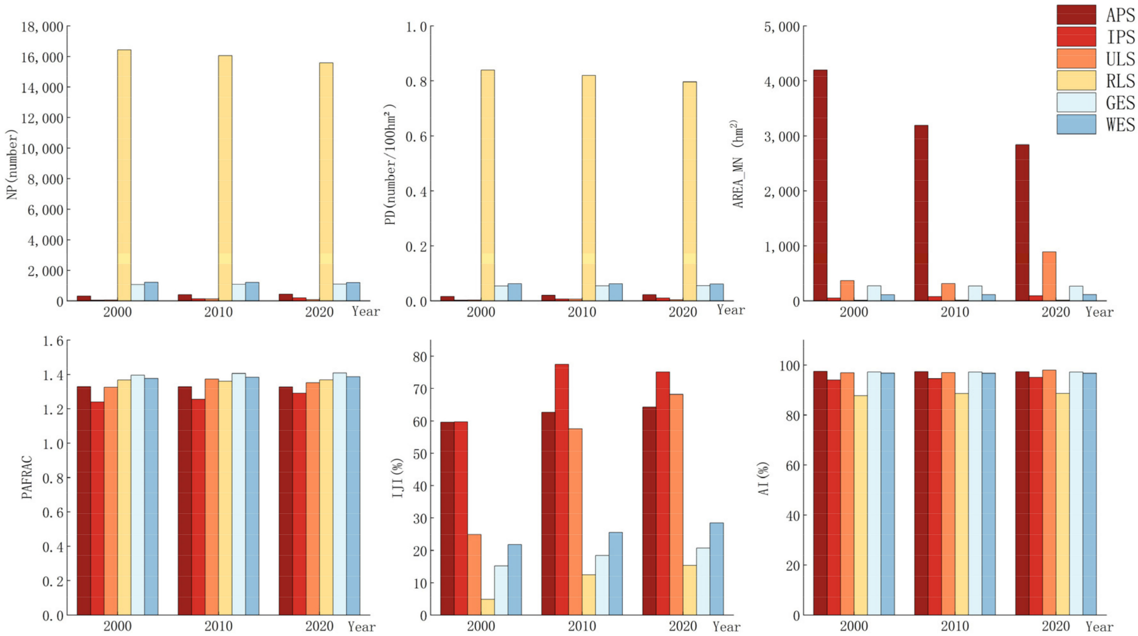

Figure 8. Type Level Index of Chaohu Lake Basin from year 2000 to 2020.

3.3.1. Driving Factors of Production–Living–Ecological Space in Chaohu Lake Basin

Table 4 shows the results of principal component analysis carried out on the driving factors of the three years. The cumulative contribution rate of the first three principal components exceeds 85%, indicating that the first three components can adequately represent the change of the original 13 factors. These three components will be further analyzed below.

Table 4. Total variance table of principal components in each year in Chaohu Lake Basin.

	Initial Eigenvalues		Extraction Sums of Squared Loadings		Rotation Sums of Squared Loadings	
	Percentage of Variance	Cumulative Contribution Rate %	Percentage of Variance	Cumulative Contribution Rate %	Percentage of Variance	Cumulative Contribution Rate %
2000	57.911	57.911	57.911	57.911	54.589	54.589
	18.806	76.717	18.806	76.717	20.359	74.948
	13.690	90.407	13.690	90.407	15.459	90.407
2010	64.759	64.759	64.759	64.759	62.719	62.719
	16.053	80.812	16.053	80.812	16.582	79.301
	14.460	95.272	14.460	95.272	15.971	95.272
2020	67.301	67.301	67.301	67.301	63.262	63.262
	18.988	86.290	18.988	86.290	16.617	79.879
	9.076	95.365	9.076	95.365	15.487	95.365

With the help of the maximum variance method, the extracted load matrix of each year is rotated to obtain the principal component factor rotation load matrix (Table 5). The results show that the first principal component has relatively large load on indicators including annual precipitation (X1), GDP (X5), GDP per capita (X6), the secondary industry value (X8), the tertiary industry value (X9), urban population (X10), and urbanization rate (X12), with the factor load all above 0.85, which reflects the urban economic development, industry, and population structure agglomeration. The second principal component has larger load on indicators including the primary industry value (X1) and the total population (X9), but the factor load level decreased significantly in 2020, indicating a gradual decrease in the influence of agriculture. The third principal component has larger load on factors including the average DEM (X3) and the average slope (X4), and the influence of terrain factors is lower than that of socioeconomic factors. Therefore, there are three main driving forces for the change of the PLES in the Chaohu Lake Basin (Table 5).

Table 5. Rotation load matrix of principal components in each year of Chaohu Lake Basin.

Serial Number	Indicating Factors	2000			2010			2020		
		F1	F2	F3	F1	F2	F3	F1	F2	F3
X1	Annual precipitation	0.947	−0.183	−0.165	0.988	−0.078	−0.088	0.952	0.270	−0.064
X2	Annual temperature	0.658	0.216	−0.051	0.988	−0.077	−0.118	−0.529	0.694	0.041
X3	Average DEM	−0.167	−0.082	0.943	−0.196	−0.119	0.906	−0.155	−0.057	0.984
X4	Average slope	−0.084	0.026	0.978	−0.151	0.053	0.974	−0.272	0.355	0.888
X5	GDP	0.875	0.456	−0.139	0.969	0.211	−0.105	0.980	0.095	−0.155
X6	GDP per capita	0.974	−0.105	−0.169	0.99	0.031	−0.068	0.972	0.159	−0.165
X7	primary industry value	−0.056	0.991	−0.026	−0.086	0.993	0.041	−0.407	−0.880	−0.126
X8	secondary industry value	0.944	0.283	−0.134	0.97	0.201	−0.111	0.964	0.001	−0.177
X9	tertiary industry value	0.94	0.278	−0.159	0.986	0.115	−0.105	0.977	0.141	−0.143
X10	Urban population	0.903	0.397	−0.105	0.943	0.292	−0.12	0.975	0.160	−0.125
X11	Total population	0.182	0.979	−0.014	0.271	0.946	−0.062	0.975	0.132	−0.111
X12	urbanization rate	0.976	−0.154	−0.104	0.991	−0.052	−0.111	0.898	−0.040	−0.307
X13	Gross output of agriculture, forestry, animal husbandry and fishery	−0.662	0.248	−0.145	−0.594	−0.244	−0.463	−0.526	−0.776	−0.099

The first principal component, the economic development and the adjustment of the industrial structure, is the dominant factor in the pattern evolution of PLES in the Chaohu Lake Basin. As the core city of Chaohu Lake Basin, Hefei City has seen an accelerated process of urbanization and industrialization, and a rapidly developed economy, especially in the secondary and tertiary industries. Its GDP increased from 303.824 billion yuan to 3000.682 billion yuan, and its total industrial output value increased from 110.045 billion yuan to 1166.394 billion yuan. In terms of industrial structure, the proportion of the primary industry in Hefei dropped from 24.1% in 2000 to 8.8% in 2018, and the proportion of the secondary and tertiary industries combined increased from 75.9% to 91.2%. Economic development and the adjustment of industrial structure have led to the reallocation of land resources among industries and the transformation of land functions. The occupation of agricultural production and ecological space by construction land has intensified, and the agglomeration of the PLES pattern distribution has been strengthened.

The second principal component is positively correlated with the output value of the primary industry and the total population, showing population growth and agricultural development. The accelerated process of urbanization has led to a large population migration, and the space of agricultural production has been transferred to the living space of cities and towns. The total population of Hefei increased from 62.78 million in 2000 to 70.83 million in 2018, of which the urban population rate increased from 28.0% to 32.7%. The increase in population has also promoted the adjustment of land use structure and industrial structure and has propelled the change in production space. At the same time, it has also led to the expansion of urban land and construction land, the intensifying occupation of the ecological space, and the fragmentation of PLES landscape. Therefore, the increase in population and the change in population structure have become the inevitable influencing factors for the transformation of PLES.

The third principal component has a large positive correlation with elevation and slope. According to the topographic characteristics of Chaohu Lake Basin, the elevation and slope are classified into plain dam ($\leq$50 m), low mountain (50–300 m), middle mountain

(>300 m), and micro slope (≤8°), gentle slope (8°–15°), and steep slope (>15°). The proportion of APS in plain and micro-slope is large, but the proportion decreases year by year. ULS and RLS are mainly located in low mountain and gentle slope zones. GES is mainly located in middle mountain and steep slope zones (Figure 9).

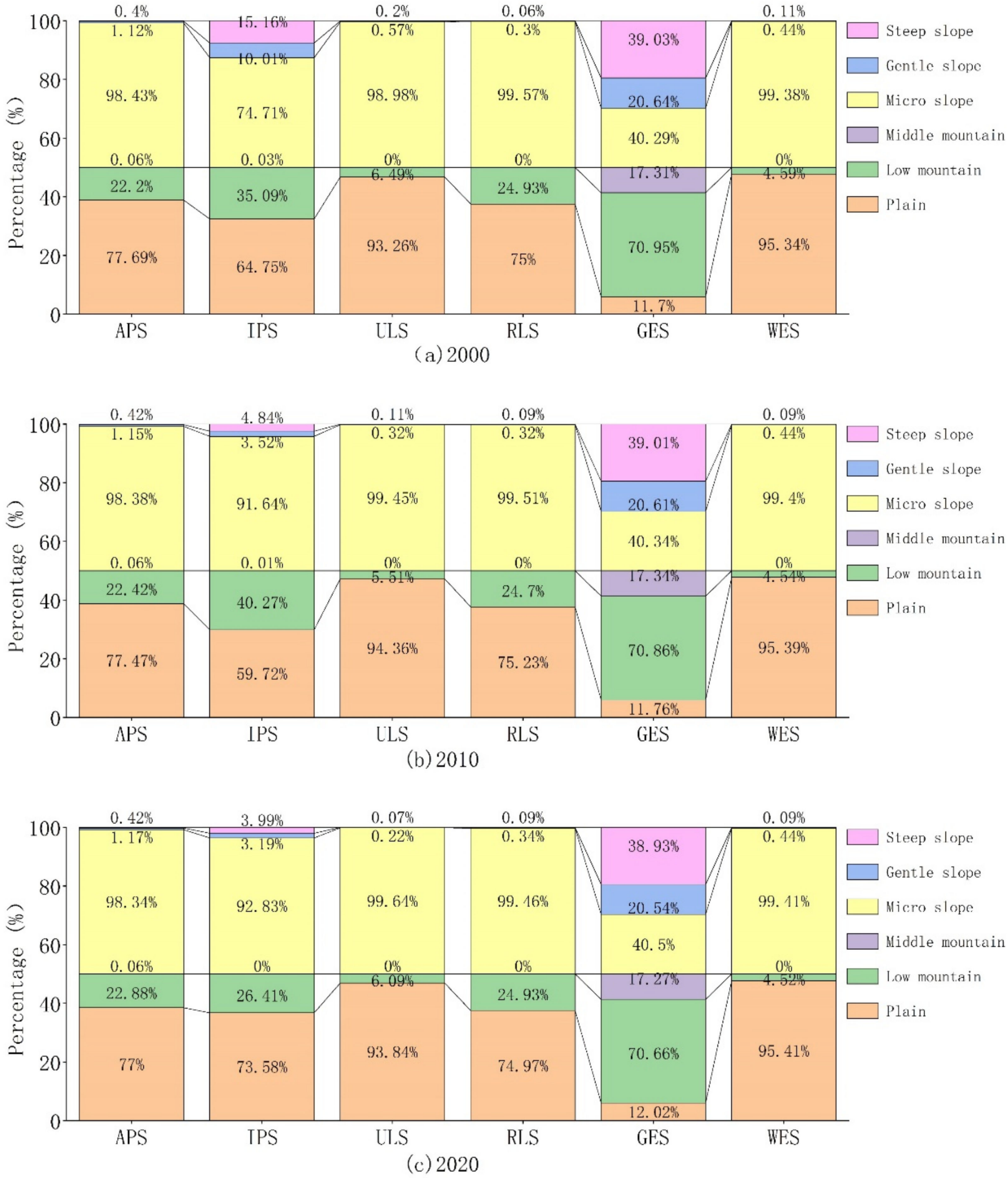

Figure 9. The area proportion of the PLES in the Chaohu Lake Basin under the conditions of slope and elevation: (**a**) 2000; (**b**) 2010; (**c**) 2020.

3.3.2. The Correlation between the Evolution and Driving Mechanism of the Production–Living–Ecological Space in the Chaohu Lake Basin

Through grey relational analysis, the degree of correlation between the type of PLES and the driving factors can be seen (Figure 10). The correlation degree of APS with annual precipitation, annual average temperature, DEM, slope, and total population is above 0.80, and natural factors and population migration have a high influence on the spatial change in agricultural production. The ULS has a high correlation with the value of the primary industry, the value of the secondary industry, and urban population, while the correlation degree of primary industry reaches 0.96 and is greatly affected by the adjustment of the industrial structure. Green ecological and WES are mainly affected by annual precipitation, annual average temperature, DEM, slope, and total population, while natural factors and human activities are the main driving factors. With the continuous advancement of urbanization, residents have moved to urban economic centers, and agricultural production labor has dropped significantly. At the same time, with the improvement of residents' requirements for living standards, urban and RLSs have expanded rapidly. The construction of water conservancy projects has also adjusted and optimized the structure of agricultural industries, lowering the rate of reduction of APS. In general, the changes in the PLES affecting the Chaohu Lake Basin are the result of multiple natural and socioeconomic factors.

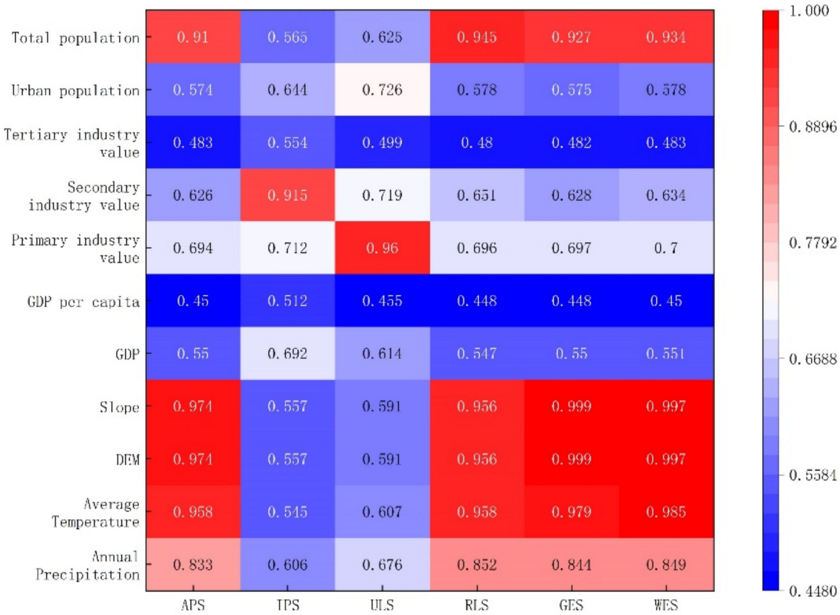

Figure 10. Correlation degree between the PLES and driving factors.

4. Discussion

4.1. The Characteristics of the PLES Evolution in the Chaohu Lake Basin

Land use/land cover change is an important component and determinant of global environmental change [45]. Since the 21st century, the study of land use change has gradually intensified in the field of global environmental change research [11,46,47]. In land use cover landscape studies, scholars from various countries have proposed different approaches, such as the use of GIS tools in the form of static (Land "Artificialization" Rate and Infrastructural Anthropization Urban Fragmentation) and dynamic (Landscape Compactness, Urban Sprawl Velocity, Contribution to New Low-Density Urban Cores, and Agricultural Transformation), The landscape diagnosis is carried out by indicators [48]. The land cover changes are comprehensively identified and deeply analyzed by the remote sensing images using the pre-classification (CVA, NDVI, NDWI) and post-classification (change detection statistics, image differencing) methods [49,50]. Among them, land use transition matrix and landscape pattern index analysis are common methods to express the spatiotemporal dynamic change process of land use. Used more widely in the study of land use and land cover evolution, these two methods can visually represent the spatial morphological changes of each space, and the internal transfer situation can be more deeply understood.

Two key features of landscape patterns are landscape heterogeneity and fragmentation, which play important roles in ecosystem change by altering landscape composition and configuration. The dominance is generally high when the SHEI values are small, reflecting that the landscape is dominated by one or a few dominant patch types. SHDI reflects landscape heterogeneity, and the higher the value, the richer the land use and the higher the fragmentation. The analysis of the landscape pattern in the Chaohu Lake Basin shows that SHDI and SHEI values are increasing, indicating that the landscape fragmentation in the Chaohu Lake watershed is intensifying and heterogeneity is increasing. It has been shown [51] that the production space is dispersed and the living space is clustered, and the production and ecological space is mainly shifted to the living space, which is consistent with the results of landscape change and landscape pattern change in this study. It can be found that under the influence of multiple driving factors such as rapid urbanization and the change in industrial structures, it has clear agglomeration characteristics. Among them, the most significant is the change from APS that primarily consists of paddy fields and dry farmland into living space. This evolution is characterized by the transformation from an expansionary mode of human activities to an agglomerative mode of human activities. Specifically, the living space areas of Yaohai District, Luyang District, Baohe District, and Shushan District located in the flat plains area expanded significantly, with an increase in agglomeration of ULSs. The reason for this is that with its rapid growth, Hefei City, as one of the cities in the demonstration zone for undertaking industrial transfer in the Wanjiang River City Belt, has seen accelerated industrial agglomeration and demand for resources and energy, the expansion of industrial industries and urban construction areas, and the strengthening of constraints on agriculture, resources, and the environment, which have caused changes in the spatial layout structure of land use, resulting in certain spatial differences. In addition, it is worth noting the continuous increase in the surface area of WES in the past 20 years, with an area increase of 0.1%. The reasons for the change can be considered as follows. First, the policy of returning farmland to the lake was implemented in the Chaohu Lake basin [33]. Second, the Chaohu Lake basin is the largest agricultural planting area in Anhui Province, and polder fields are an important form of agricultural water conservancy in the Chaohu Lake basin. Most of the area around Chaohu Lake is dominated by polder fields, with ditches dug, lake water introduced, and an artificial water network formed inside the polder fields, which both makes the surface area increase and is a manifestation of human ecological wisdom. Third, a large Dafang Ying reservoir was built in the Hefei city area northwest of Chaohu Lake. In these processes, the frequent changes in the ecological space of production and life have led to the interlocking of urban spatial structures, and the pattern of the "ecological–production–living space" in the lake basin tends to be complicated.

4.2. The Driving Mechanism of Production–Living–Ecological Space Evolution in Chaohu Lake Basin

Based on the above discussion and analysis, this study finally constitutes a "process–pattern–driver" framework for analyzing the evolution of the PLES in the Chaohu Lake basin (Figure 11). It shows the area conversion between the PLES and the different types of driving factors that affect the changes of the PLES. In terms of the driving mechanism, most of the previous methods such as geographic probes [52,53], Pearson correlation analysis [54], and regression analysis [42] have been used to investigate the correlation between land use change and factors, but most of these methods require a large amount of data and samples obeying a typical probability distribution, requiring a linear relationship between the data of each factor and the data of the system characteristics and the factors being independent of each other, which has certain limitations. There are limitations.

This paper proposes a method that combines principal component analysis with gray correlation analysis, which is what makes this study different from others. Firstly, the principal component analysis method was used so that each principal component can reflect most of the changes in the original data, overcoming the subjective arbitrariness of the traditional method and identifying the main driving indicators of the Chaohu Lake basin. Secondly, the improved gray correlation analysis method was used to analyze the natural, socioeconomic, and demographic factors in the Chaohu Lake basin. The correlation degree between each spatial type change and each driving factor was derived, which can better spatial planning management. The analysis of natural and socioeconomic factors on the drivers of changes in the PLES in the Chaohu Lake Basin identified three main component indicators of changes in the Chaohu basin, one of which is economic development and industrial structure; the other is population growth and agricultural development; and the third is natural factors. This is consistent with the results of a large number of studies [35]. Among them, population, climate (precipitation and temperature), and topography (elevation and slope) are the main driving factors of APS. The large area of Chaohu Lake basin is plain, the topography is less undulating, and it is a subtropical monsoon season, so the conditions of water, light, and heat required for agricultural cultivation are suitable, and the space for agricultural production is developed. However, with the development of urbanization and industrialization, the growing population, and the increased demand for food, the contradiction between urban construction, industrial production, and agricultural cultivation has intensified, and the arable land in the basin has decreased by 6.05%. In the study by Ren [25], it has also been shown that human activities, temperature, and precipitation have some influence on the change of cultivated land. The results show that Chaohu Lake Basin is greatly affected by natural factors, and the proportion of social and economic factors is gradually increasing; therefore, attention should be paid to social and economic factors in the subsequent development.

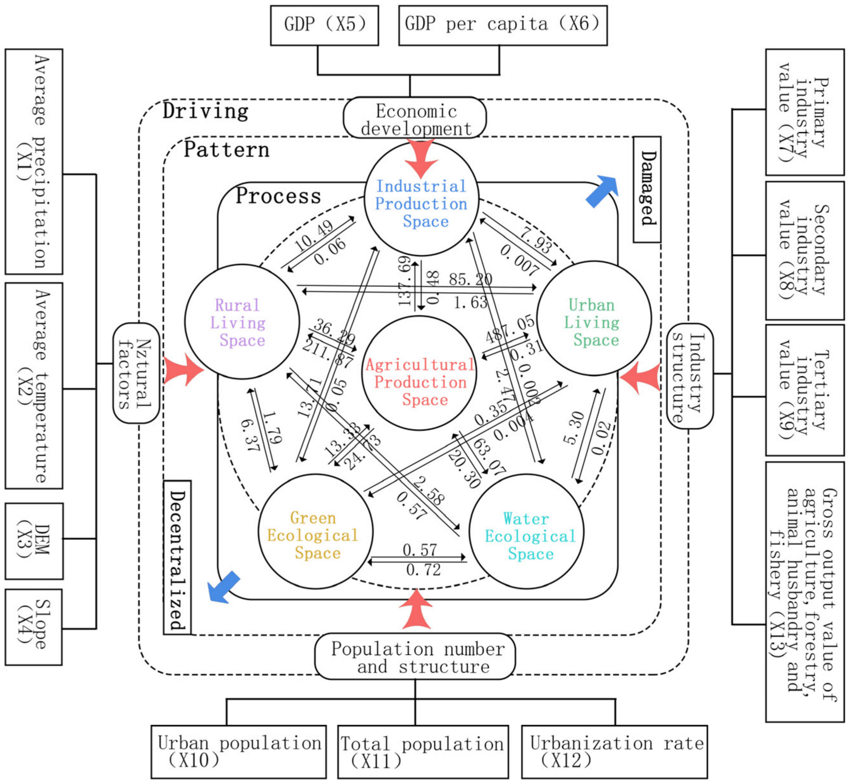

Figure 11. The driving mechanism of PLES evolution in Chaohu Lake Basin.

In addition, some research results also show that political factors such as national strategies, policy guidelines, laws and regulations, and development planning guide the direction and speed of social and economic development and determine the direction and speed of the evolution of the spatial pattern of production and living ecology [35]. The evolution of China's land policy has experienced the transformation from strictly controlling the quota of cultivated land development and utilization to intensive land utilization and development, from paying attention to the quantity of land utilization to paying attention to the quality of land utilization, and from only paying attention to cultivated land protection to comprehensive ecological protection. Among them, the implementation of the policy of returning farmland to forests has promoted a major change in China's ecological construction. The first round of the project began in 1999 and lasted for 15 years. A total of 92,667.13 km^2 of cropland to forest and grassland was implemented. Under the influence of the policy of returning cropland to the forest, the APS in the Chaohu Lake Basin flowed into GES from 2000 to 2020, and the area of WES was

36.03 km^2 and 47.23 km^2. The vegetation coverage increased, the interception and water storage capacity of precipitation increased, and soil erosion slowed down. The policy factor is an influential factor worthy of attention for the change of PLES. In order to achieve sustainable development, it is necessary to interpret the policy, coordinate the contradiction between the ecological environment and social development in the process of PLES, and avoid the irrationality of spatial planning.

4.3. Implication on the Optimization of Landscape Space Pattern

According to the analysis results, in the future economic development ecological civilization construction, land use can be regulated according to the actual conditions in natural factors, economic realities, and national policies, clarifying territorial spatial planning and development strategy. Rationally adjusting the industrial spaces, optimizing the layout of living spaces, and strengthening the protection of ecological spaces can promote the territorial spatial development pattern that accomplishes efficient production space, comfortable living space, and beautiful ecological space. To this end, the following three suggestions can help optimize the PLES pattern in the Chaohu Lake Basin:

(1) Scientifically delineate the red lines of PLES in the Chaohu Lake Basin, optimize and adjust the production-led territorial development model, and accelerate the construction of a sustainable landscape pattern that is led by living space, prioritizes ecological space, and balances the PLES.

(2) Carry out regional basic farmland protection in the Chaohu Lake Basin, prohibit reclamation of the lake, and effectively control the expansion of urban construction land; strengthen the protection of forest land resources in the southwest of the Chaohu Lake Basin, speed up the control of soil erosion, and strengthen the management of production space and living space in the Chaohu Plain area, avoiding the accelerated landscape fragmentation caused by the interference of human activities.

(3) Elevate the land utilization level, tap into latent construction land stock, promote the optimization and integration of urban construction through measures such as the redevelopment of low-efficiency urban lands and the reclamation of abandoned industrial and mining lands, economize and intensify land usage, protect environmental and ecological land of the urban areas, and implement the organic combination of urban development land, green belt zones, and basic farmland, making Chaohu Lake Basin a demonstration area for green development and ecological civilization.

4.4. Strengths and Limitations

Previous studies on the spatiotemporal evolution characteristics of the PLES have mostly focused on urban [55], mountainous, and county regions [56], mostly exploring the spatiotemporal evolution characteristics and driving mechanisms of the regions based on land use, and lacking in the overall spatial analysis of the functional space. Lake basins are fragile ecological areas, densely populated areas, and highly intensive land use areas on a global scale. In addition, the Chaohu Lake Basin is a typical lake basin, which has both ecological vulnerability and economic development center. Therefore, on this basis, this research explores the functional space of the Chaohu Lake basin from the perspective of territorial space. It further explores the main driving indicators of the spatiotemporal evolution of each spatial type and their degree of correlation with each driving factor by analyzing the transfer of functional spatial structures and landscape pattern indices, using principal component analysis and gray correlation analysis. This can, to a certain extent, provide a more reasonable basis for the production, living, and ecology. To a certain extent, it can also help formulate more reasonable spatial planning policies for the balanced development of production, life, and ecology in the Chaohu basin.

Due to data acquisition and technical reasons, this study used land use cover classification data to classify the functional attributes of land use in the Chaohu Lake Basin in the PLES classification system that is not precise enough, because different regional geographical environment and social economy development will affect the region spatial structure function. Simple classification based on the territorial space standard classification system may result in unclear identification of regional spatial structure, and still have some room for improvement. In the future, relevant literature and policy documents should be consulted further. On the one hand, more attention should be paid to the accuracy of functional space classification and the selection of landscape pattern indicators in the construction of territorial spatial classification system. On the other hand, it is necessary to improve the richness and diversity of index factors. Social policy factors can be included, and the selection of driving index factor should be explored the more deeply in the later research. The research objects this research selected has certain representative and typicality, with double identity on the center of the ecological vulnerability and economic development. The driving factors selected are fundamental and practical, and the results of this paper can provide reference and empirical basis with the natural, economic development of the Chaohu Lake Basin, and it will be easier to put forward corresponding planning strategies for different functional spaces.

5. Conclusions

Based on the types of land use and cover, this paper divided the land space into APS, IPS, ULS, RLS, GES, and WES according to the functional attributes, and obtained the spatial distribution map of PLES in Chaohu Lake Basin. From 2000 to 2020, the structure of functional space in Chaohu Lake Basin has changed greatly, and the change intensity from high to low is as follows: APS, ULS, IPS, RLS, WES, and GES. Among them, the changes of APS and ULS are the most obvious. The area of APS shows a continuous downward trend, while the area of ULS continues to increase, and the APS mainly flows to ULS. According to the landscape pattern index analysis of PLES; the discrete degree of APS increases; the IPS, ULS, RLS, and WES tend to be regular and centralized; and the overall space of Chaohu Lake Basin tends to be fragmented and decentralized. According to the spatiotemporal evolution characteristics of PLES in Chaohu Lake Basin, this paper studies the correlation relationship between function space type and driving factors in the use of principal component analysis and grey correlation analysis. Furthermore, the result is in addition to natural factors, social economic factors, and human activities, which play an important role. In addition, the role of the social economic factors is increasing; however, the natural factors are still greater than the social and economic factors, especially the restriction of terrain to the spatial distribution of this area.

Author Contributions: Xu Zhou and Songnian Li contributed to the conception and design of the study; field and lab experiments, data collection, and analysis were performed by Ruyi Zhang, Baojing Wei and Xu Zhou; the manuscript was written by Ruyi Zhang, Xu Zhou and Songnian Li. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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