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Spatial-temporal pattern of change in production-living-ecological space of Nanchong City from 2000 to 2020 and underlying factors

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Abstract This study analyzed the spatial-temporal change pattern and underlying factors in production-living-ecological space (PLES) of Nanchong City, China, over the past 20 years using historical land use data (2000, 2010, 2020). A land use transfer matrix was calculated from the historical land use maps, and spatial analysis was conducted to analyze changes in the land use dynamics degree, standard deviation ellipse, and center of gravity. The results showed that there was a rapid spatial evolution of the PLES in Nanchong from 2000 to 2010, followed by a stabilization in the second decade. The transfer of ecological-production space occurred mainly in the Jialing and Yilong River basins, while the reduction of production space and the increase of living space were most prominent in the intersection of three districts (Shunqing, Jialing, and Gaoping districts). The return of production-ecological space was observed in the south and northeast of Yingshan, and there was little notable transfer of other types. The distribution of production space in Nanchong evolved in a north-south to east-west trend, with the center of gravity moving from Yilong to Peng'an County. The living space and production space expanded in a north-south direction, and the center of gravity position was in Nanbu, indicating a more balanced growth or decrease in the last 20 years. The changes in the spatial-temporal pattern of PLES in Nanchong were attributed to the intertwined factors of national policies, economic development, population growth, and the natural environment. This study introduced a novel approach towards rational planning of land resources in Nanchong, which may facilitate more sustainable urban planning and development.

Keywords Production-living-ecological space (PLES) · Pattern evolution · Migration · Driving force · Principal component analysis

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Introduction

In recent years, urbanization and urban sprawl have significantly affected land use land cover (LULC), transforming agricultural or forested areas around cities into built-up zones. This conversion has the potential to negatively impact agricultural production and ecosystem services. Hence, the "production-living-ecological space" (PLES) classification system has been proposed to categorize LULC into "production space," "living space," and "ecological space" (Duan et al., 2021). These categories are designed to address metropolitan regions' demands for economic, residential, and environmental protection (Li & Fang, 2016). These areas serve different functions, but they are interconnected and interdependent, forming a foundation for achieving sustainable urban development and improving the standards of living.

In recent decades, China has experienced a significant increase in urbanization, which rose from 17.9% in 1978 to 63.89% in 2020 (Yu, 2021). The rapid urbanization has also brought up problems such as spatial structural imbalance, tense human-environment relations, and ecological environments degradation. The urbanization process generally prioritized the land's livability and production functions over ecological functions in China (Yao et al., 2021), leading to a rapid expansion of urban production activities and living spaces over ecological spaces. This encouraged intense competitions among PLES types (Zou et al., 2021) and posed serious negative effects on human living quality and environmental safety, hindering healthy and orderly regional and national economic development (Wu et al., 2022). Therefore, coordinating the rational allocation of land resources to promote sustainable socio-economic development becomes a critical issue for countries worldwide (Zhang et al., 2022).

At the turn of the twentieth century, the urban planning theories such as "ribbon cities," "garden cities," and "organic evacuation" (Kharchenko et al., 2018; Morris et al., 2016; Sharifi, 2016; Xing & Brimblecombe, 2019) have been increasingly applied in urban planning in China. Consequently, the Chinese academic community recognized the significance of ecological civilization construction in land space planning and introduced concepts, such as PLES and production-living-ecological function. Current research on PLES focuses mainly on functional classification (Zhang & Xu, 2017), layout optimization, and different scales (Xiao et al., 2022), as well as conceptual and theoretical frameworks (Fu et al., 2021; Lin et al., 2022; Zhao & Zhao, 2023), functional changes (Liu et al., 2023), evaluation models (Liao et al., 2019; Nian et al., 2014), and factors that affect the change of PLES (Deng & Yang, 2021). All of these primarily involve metropolitan area (Yang et al., 2020), administrative regions (Chen et al., 2021), and watersheds. The research focus is on the division of PLES based on the main functional zones (Tian et al., 2020; Xu et al., 2022), ecosystem theory, and land use (Liu & Hao, 2003; Lovell et al., 2010). In addition, some scholars researched the optimization of PLES layout by evaluating suitability and integrating multiple plans (Liao et al., 2022). However, most studies research on PLES mainly concerned the central (Li et al., 2022), eastern (Wang et al., 2023), and northwestern regions of China (i.e., the regions with the most rapid rates of urbanization). There is little research has been conducted on the PLES and its evolution over time in the southwestern region of China.

With the establishment of the Chengdu-Chongqing Economic Zone (Wang et al., 2022) and the new development pattern of dual circulation, Nanchong is gradually becoming a key node in the new Western Land-Sea Corridor (Yin et al., 2023) (Nanchong Municipal Government Office) (https://nanchong.gov.cn/), ushering in a period of high-level development (Dong et al., 2014). However, the rapid economic growth has also led to serious ecological problems in Nanchong, such as deterioration of natural forest land, a decline in the amount of forest cover, and intensified soil erosion (Zhang et al., 2022). Notably, the annual direct economic losses caused by floods exceed 288 million RMB (https://yjt.sc.gov.cn/). Therefore, this paper examined Nanchong City in southwest China as a case study, analyzing the spatial-temporal change pattern and underlying factors of PLES from 2000 to 2020. The analysis was conducted using the land use transfer matrix, land use dynamic degree, and center of gravity transfer analysis with historical land use datasets. Additionally, this paper provided new research directions to optimize the PLES of Nanchong. Specifically, the purposes of this study are (1) to analyze the spatial-temporal evolution characteristics of PLES in Nanchong, (2) to use the center of gravity transfer model to analyze the distribution

characteristics and changes in PLES in Nanchong, and (3) to investigate the impact of national policies, population, economic development, and natural environmental factors on the PLES in Nanchong.

Materials and methods

Overview of the research area

Nanchong, nestled in the northeastern part of Sichuan Province, China, is strategically positioned in the middle section of the Jialing River. Its borders are shared with Dazhou, Guang'an, Mianyang, and Suining to the east, south, west, respectively, and with Guangyuan and Bazhong to the north (Dong et al., 2014). Its area covers 12,500 km² including three districts, five counties, and one city under its jurisdiction, with a subtropical humid monsoon climate.

The entire area of Nanchong City is predominantly characterized by a hilly landscape. The terrain slops gradually from north to south, with an altitude range of 256~889 m (Fig. 1).

Nanchong is designated as a regional center city in the "Chengdu-Chongqing Urban Cluster Development Plan" and serves as the economic, logistics, trade, and financial core in the northeastern part of Sichuan province. Since China implemented the "Belt and Road" strategy in 2018, Sichuan became an essential growth pole in China's Western region, with Nanchong playing an indispensable role in it. The "13th Five-Year Plan" for the environmental protection in Nanchong City emphasizes the importance of the ecological environment preservation over the next decade. The city aspires to become a modern ecological city with an efficient ecological economy, beautiful ecological environment, flourishing ecological culture, pleasant ecological living conditions,

Fig. 1 Location map of study area. **a** The Sichuan is located in southwestern China. **b** The Nanchong City is located in the northeastern Sichuan. **c** Location map of Nanchong City
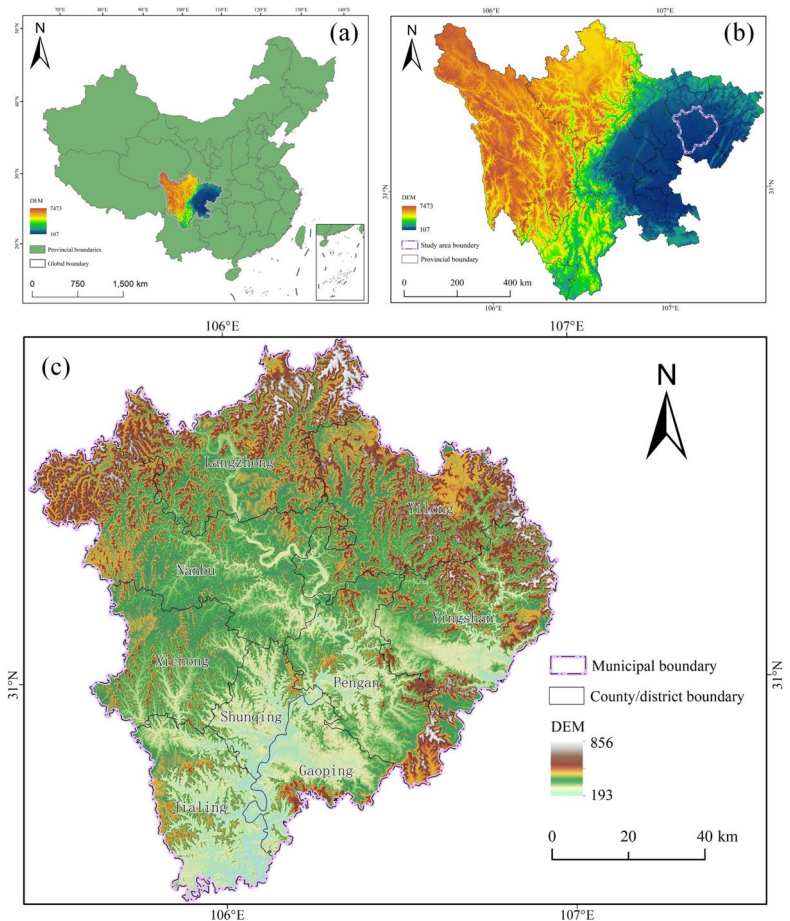
and harmonious coexistence between humans and nature. It aims to be recognized as a key ecological city nationwide. Therefore, conducting to analyze the spatial-temporal evolution characteristics of PLES in Nanchong over the past 20 years is of great significance.

Data source and preprocessing

This research used the land use data from the Chinese Academy of Sciences Resource and Environment Science Data Center (https://www.resdc.cn), which has an overall accuracy higher than 80%, with a spatial resolution of 30 m. For this study, the original land use data was reclassified into three classes (production, living, and ecological spaces) according to the PLES classification system proposed by Liu et al. (2010). The PLES maps from 2000, 2010, and 2020 were then imported into ArcGIS 10.2, and ASTER GDEM 30M data with a spatial resolution of 30 m from the Geospatial Data Cloud platform (https://www.gscloud.cn/).

This study combined the research outcomes (Feng et al., 2022; Gao et al., 2022) of the spatial-temporal influencing factors of PLES to analyze the dominant driving factors influencing changes in the PLES of Nanchong City. From the statistical yearbook of Sichuan Province, 11 driving factors were selected from three aspects, namely, urban scale (total population, population growth rate, urbanization rate), economic development (GDP, proportion of primary industry, proportion of secondary industry, proportion of tertiary industry, fixed asset investment, gross output of agriculture, forestry, animal husbandry and fishery), and the natural environment (annual precipitation, annual temperature). An evaluation index system was subsequently constructed. All the spatial data were resampled in ArcGIS to unify the spatial resolution to 30m. The coordinate system is WGS_1984_UTM_Zone_48N.

Methods

This study established a spatial classification system for the production, living, and ecological spaces (PLES) of Nanchong City, utilizing land use data from 2000, 2010, and 2020. Three methods, namely land transfer matrix, land use dynamic degree, and gravity model, were utilized to analyze

the PLES' structural and spatiotemporal evolution characteristics. This study identified eleven potential influencing factors extracted from natural, social, and economic factors through principal component analysis. The study further examined the underlying factors contributing to the spatial-temporal patterns of PLES in Nanchong City from 2000 to 2020. Figure 2 illustrates the entire procedure.

Production-living-ecological space classification method

There is currently no standardized classification system for PLES maps. Thus, this study utilized the research findings of Liu et al. (2017) and other scholars to reclassify 19 secondary land use types in the study area into corresponding PLES classes for Nanchong City (Table 1).

The categories of paddy fields, dry land, canals, reservoirs, and other developed lands were classified as production space. Meanwhile, urban land and rural settlements were designated as living space. Ecological space comprises all secondary land categories, excluding production and living spaces.

Transfer matrix of PLES

To quantitatively analyze the evolutionary characteristics of land use within a specific area over a defined period, the land use transfer matrix method is commonly employed. The study mainly focused on examining the interconversion among different land use types and analyzing the internal process of land change (Takada et al., 2010). By utilizing the transfer matrix method, the study analyzed the spatial-temporal pattern changes of PLES in Nanchong City and also demonstrated the spatial conversions that took place. This approach offered a direct and clear comprehension of the modifications that occurred in PLES in Nanchong City. The formula is shown as follows:

$$S_{ij} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & \cdots & S_{1n} \\ S_{21} & S_{22} & S_{23} & \cdots & S_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ S_{n1} & S_{n2} & S_{n3} & \cdots & S_{nn} \end{bmatrix} \tag{1}$$
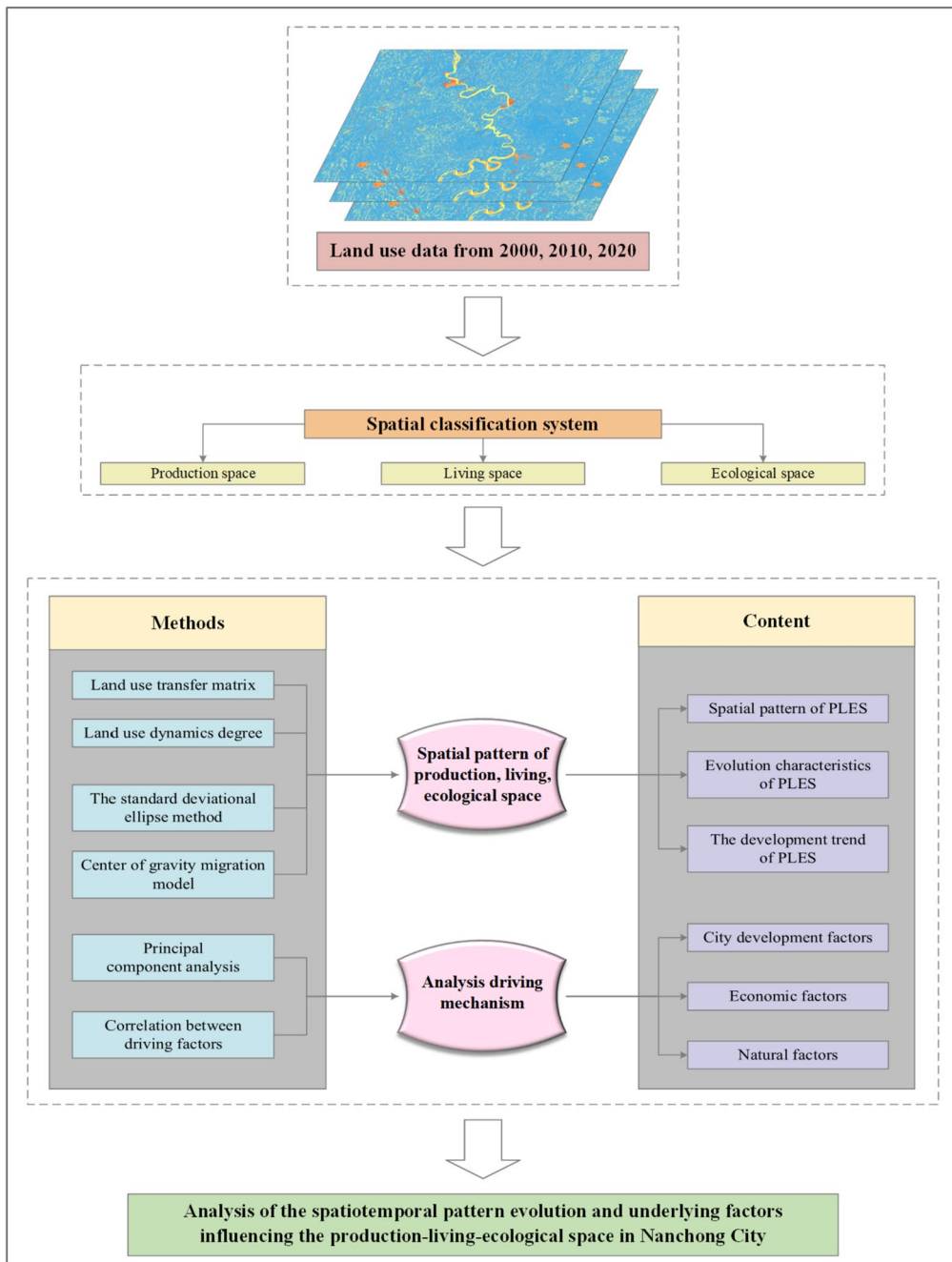
Fig. 2 The overall process of the methodology

where S_{ij} represents the overall extent of the study area (km²), n denotes the total number of land use types, and i and j represent the initial and final land use types, respectively, during the study period.

Land use dynamic degree

The land use dynamic degree (LU) model, consisting of both single and integrated land use dynamic degrees, is employed to examine alterations in land use (Liu et al.,

Table 1 The PLES classification method of Nanchong City

Primary classification	Corresponding land use type
Production space	Paddy field, dry land, canals, reservoirs, other construction land
Living space	Urban land, rural settlement
Ecological space	Woodland, shrub forest, sparse woodland, other woodland, (high, medium, low) coverage grassland, lakes, beaches, swampy, bare land, bare rock texture

2003). LU calculation enables identifying the quantities and changes of individual or overall land categories in a study area over a specified temporal period. The single dynamic degree index of land use enables a numerical portrayal of the rate at which land use changes occur within a particular region. This index is crucial for comparing regional variations and analyzing trends. The integrated dynamic degree index of land use captures the transfer rate among land categories throughout the research period, providing an indication of the overall changes in all land categories over time. This paper employed LU to study the changes in individual or overall spatial land categories in the PLES of Nanchong city within a specified time frame. The scale of the calculated value indicates the degree and speed of changes, where a larger value implies a more intense and rapid degree of change. The formula is shown as follows:

$$L = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\% \qquad (2)$$

$$LC = \frac{\sum_{i=1}^{n} \Delta LU_{i-j}}{2 \sum_{i=1}^{n} LU_i} \times \frac{1}{T} \times 100\% \qquad (3)$$

where L and LC represent the single and integrated land use dynamic degree, respectively. Additionally, U_a and U_b correspond to the PLES land categories' area during the initial and final stages of the study period, respectively. The research period is denoted by T. Furthermore, LU_i represents the land use area of the ith type of PLES during the initial study period, whereas ΔLU_{i-j} signifies the absolute area of change from land category i to j during the study period T.

Gravity center migration of PLES

The concept of center of gravity initially emerged from research on population and economics.

Subsequently, researchers began to focus on the migration of land use gravity, which intuitively reflects the spatiotemporal changes in land use patterns within specific regions.

Current studies utilize the standard deviation ellipse and the land use gravity center migration model (Gong, 2002) to investigate the distribution patterns and change differences of PLES spatial areas. This study illustrated the PLES spatial areas trajectory of gravity migration through a diagram for further examination. The center of gravity is given as:

$$X_t = \frac{\sum_{i=1}^{n} \left(C_{ti} \times X_i \right)}{\sum_{i=}^{n} C_{ti}} \qquad (4)$$

$$Y_t = \frac{\sum_{i=1}^{n} \left(C_{ti} \times Y_i \right)}{\sum_{i=}^{n} C_{ti}} \qquad (5)$$

where X_t and Y_t represent the geographical coordinates (latitude and longitude) of the center of gravity for the spatial distribution of the PLES category in a year t, C_{ti} represents the area of the ith patch corresponding to this specific type of PLES spatial pattern, and X_i and Y_i denote the geographical coordinates the center of gravity for the ith patch.

Principal component analysis

Examination of the driving force of PLES reveals a diverse range of factors. Although this comprehensive approach provides valuable insights, it may generate redundant data, thereby impeding the analysis process by adding complexity and computational intensity. Additionally, the presence of correlated data may undermine the reliability and accuracy of the analysis of the driving mechanism.

Principal component analysis (PCA) employs the concept of dimensionality reduction to convert numerous metrics into a limited set of composite metrics,

thereby preserving the maximum amount of information from the data while eliminating redundancy (Guo et al., 2022; Sun et al., 2021; Zhang et al., 2022). It employs a linear transformation to convert a set of interrelated metrics into an independent set arranged in descending order of variance, while maintaining the total variance of the variable's constant. The initial variable with the greatest variance is designated as the first principal component (F1), while the second principal component (F2) is the next highest variance metric uncorrelated with the first. This process continues with every subsequent principal component, with n principal components extracted for n variables. Once the PCA is complete, each extracted principal component can be renamed to reflect the unique contribution of each indicator based on expert knowledge and context-specific meaning. The selection of each principal component is as follows:

$$\begin{cases} F_1 = c_{11}Z_1 + c_{12}Z_2 + \cdots + c_{1n}Z_n \\ F_2 = c_{21}Z_1 + c_{22}Z_2 + \cdots + c_{2n}Z_n \\ \qquad\qquad\qquad \vdots \\ F_n = c_{n1}Z_1 + c_{n2}Z_2 + \cdots + c_{nn}Z_n \end{cases} \qquad (6)$$

where F_i represents the ith principal component, with i ranging from 1 to n; c denotes the eigenvector associated with the eigenvalues of the covariance matrix; Z represents the normalized values of the initial variables; and for each i, it holds that $c_{i1}^2 + c_{i2}^2 + \cdots + c_{in}^2 = 1$.

Results and analysis

Spatial-temporal dynamics of the PLES in Nanchong city

Analysis of the structural transformations of PLES

Figure 3 and Table 2 show that between 2000 and 2020, the production space area in Nanchong City declined by 2% (from 10,959.51 to 10,710.80 km^2), while the living space area increased by over 77% (from 87.77 to 156.08 km^2). Although the ecological space area trended upwards initially, it eventually decreased slightly. However, the overall change was on an upward trend (increasing from 1427.59 km^2 in 2000 to 1608.17 km^2 in 2020).

The ecological space in Nanchong City grew most significantly in Yingshan and Yilong Counties in the northeast region of the city. The city's urban regions experienced a decline in production space during the same time, while the living space grew significantly, with the most significant growth occurring in the western part of the study, including Shunqing, Jialing, and Gaoping Counties. The living space in other counties and cities in the Nanchong region also experienced scattered increases during the same time.

Evolution of the spatial-temporal pattern of PLES

Table 3 shows that the PLES in Nanchong City has undergone a total transfer of 1059.85 km^2 between
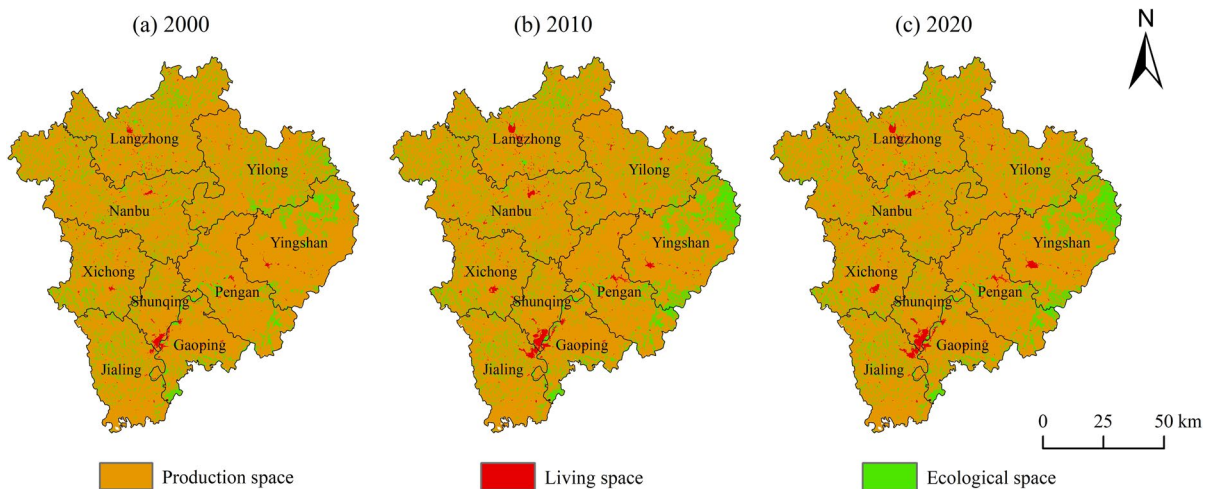

Fig. 3 The pattern of PLES in Nanchong City in 2000 (**a**), 2010 (**b**), 2020 (**c**)

Table 2   Changes in the spatial extent of PLES in Nanchong City from 2000 to 2020

	2000		2010		2020	
	Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)
Production space	10959.51	87.85%	10718.77	85.92%	10710.80	85.86%
Living space	87.77	0.70%	145.04	1.16%	156.08	1.25%
Ecological space	1427.59	11.44%	1611.26	12.92%	1608.17	12.89%

2000 and 2020, which is 8.50% of the city's entire land area. The transferred area used for productive use totaled 652.75 km^2. Among the areas that were changed, 87.17% was converted to ecological space, while 12.83% was converted to residential space. In contrast, the area that was converted to productive space was only 404.11 km^2, which represents a difference of 248.64 km^2. Only a small fraction of the living space, specifically 17.11 km^2, was converted to other uses. However, the reconversion to residential use accounted for a high value of 85.41 km^2, leading to a difference of 68.31 km^2. This conversion accounted for 77.83% of the original living space, and about 98.02% and 1.98% of this difference was realized from productive and ecological space, respectively. The transferred ecological space area was calculated to be 389.99 km^2 while the area converted to ecological space was found to be 570.32 km^2. This difference of 180.33 km^2 reflects only 0.23% of the

productive space conversion and 0.23% of residential area conversion.

Table 4 shows the results of the PLES types in Nanchong City, obtained by using the formula of single land use dynamic degree (L). During the period from 2000 to 2020, the total area in Nanchong City experienced an increase of 68.31 km^2, corresponding to a dynamic degree of 3.71%. The significant increase in area took place particularly between 2000 and 2010, accounting for 83.84% of the total area increase, with a high dynamic degree of 5.87%. Over the same period, there was a substantial decline in the area dedicated to production space, experiencing a decrease of 248.71 km^2 with a dynamic degree of −0.11%. The area exhibited a rapid decline, which was subsequently followed by a gradual stabilization. From 2000 to 2020, the ecological space in Nanchong City expanded significantly by 180.58km^2, with a dynamic degree of 0.60%. The most significant

Table 3   Production-living-ecological space change transfer matrix from 2000 to 2010 (km^2)

		2010			Total area
		Production space	Living space	Ecological space	
2000	Production space		60.71	283.68	344.39
	Living space	3.67		0.48	4.15
	Ecological space	99.85	0.71		100.56
Total area		103.52	61.42	284.16	
		2020			Total area
		Production space	Living space	Ecological space	
2010	Production space		31.40	356.81	388.21
	Living space	20.96		1.65	22.61
	Ecological space	359.30	2.24		361.54
Total area		380.26	33.65	358.46	
		2020			Total area
		Production space	Living space	Ecological space	
2000	Production space		83.72	569.03	652.75
	Living space	15.82		1.29	17.11
	Ecological space	388.30	1.69		389.99
Total area		404.11	85.41	570.32	

Table 4 The single dynamic degree of PLES in Nanchong from 2000 to 2020

	2000–2010		2010–2020		2000–2020	
	Area change (km^2)	Single dynamic degree (%)	Area change (km^2)	Single dynamic degree (%)	Area change (km^2)	Single dynamic degree (%)
Production space	−240.75	−0.20%	−7.97	−0.01%	−248.71	−0.11%
Living space	57.27	5.87%	11.04	0.68%	68.31	3.71%
Ecological space	183.67	1.16%	−3.09	−0.02%	180.58	0.60%

Table 5 The integrated dynamic degree of PLES in Nanchong from 2000 to 2020

Period	2000–2010	2010–2020	2000–2020
Integrated dynamic degree	0.18%	0.01%	0.09%

increase of 183.67km^2 and a dynamic degree of 1.16% occurred between 2000 and 2010. However, from 2010 to 2020, there was a small decrease of 3.09km^2, with a dynamic degree of −0.02%. As a result, the ecological space in Nanchong City experienced a rapid expansion from 2000 to 2020, followed by a slight decrease. Nevertheless, the area remained relatively stable despite this reduction.

Table 5 shows the results of the PLES types in Nanchong City, which was obtained by using the formula of integrated land use dynamic degree (LC). Over the span of 20 years, from 2000 to 2020, the dynamic rate for LC in the PLES of Nanchong City was registered at 0.09%. Notably, during the first decade of this time of period, the LC value for the PLES in Nanchong City was found to be 0.18%. Subsequently, during the second decade spanning from 2010 to 2020, the LC value for the PLES in Nanchong City decreased significantly to 0.01%. An analysis of the LC value over the years indicates that the rate of evolution of the PLES in Nanchong City has been notably on the rise since 2000 and then stabilized.

Figure 4 depicts the spatial-temporal variations in the distribution of PLES types within Nanchong City from 2000 to 2020. During the timeline in this study, the transition from production spaces to ecological spaces on a larger scale occurred primarily in the southern and northeastern regions of Yingshan County. This transformation was significantly influenced by official policies such as "conversion of farmland to forest" and various "greening initiatives" that expedited the shift towards ecological spaces. On the other hand, the transition from production spaces to living spaces was principally concentrated at the intersection of the Shunqing District, Gaoping District, and Jialing District. This particular region is located at the heart of Nanchong, which is why its urban construction and progress accelerated significantly. Moreover, the shift from ecological spaces back to production spaces was predominantly observed in the Jialing River basin and the nearby areas of Yilong River. The main rationale behind this conversion is its proximity to water sources, which greatly supported the production space construction. Other types of space changes were relatively small and scattered throughout the study region.

Development trend of PLES in Nanchong city

The spatial center of gravity coordinates for PLES in Nanchong City from 2000 to 2020 was computed using the standard deviation ellipse and land use center of gravity model, as presented in Table 6. A migration map was produced to examine the distribution characteristics and variations of PLES within Nanchong City (Fig. 5).

The standard deviation ellipse of the production space in Nanchong City had a south-north orientation in 2000, whereas it was oriented east-west in 2010 and 2020. The major axis of the ellipse experienced an increase in length in 2020, while the minor axis exhibited a decrease, compared to 2000. This change indicates that the production space in Nanchong City shifted from a south-north to an east-west distribution. From 2000 to 2010, the center of gravity of the production space moved from Yilong County to the south-east, reaching the junction of Peng'an County and Yingshan County. Subsequently, in 2020, the center of gravity moved a short distance further
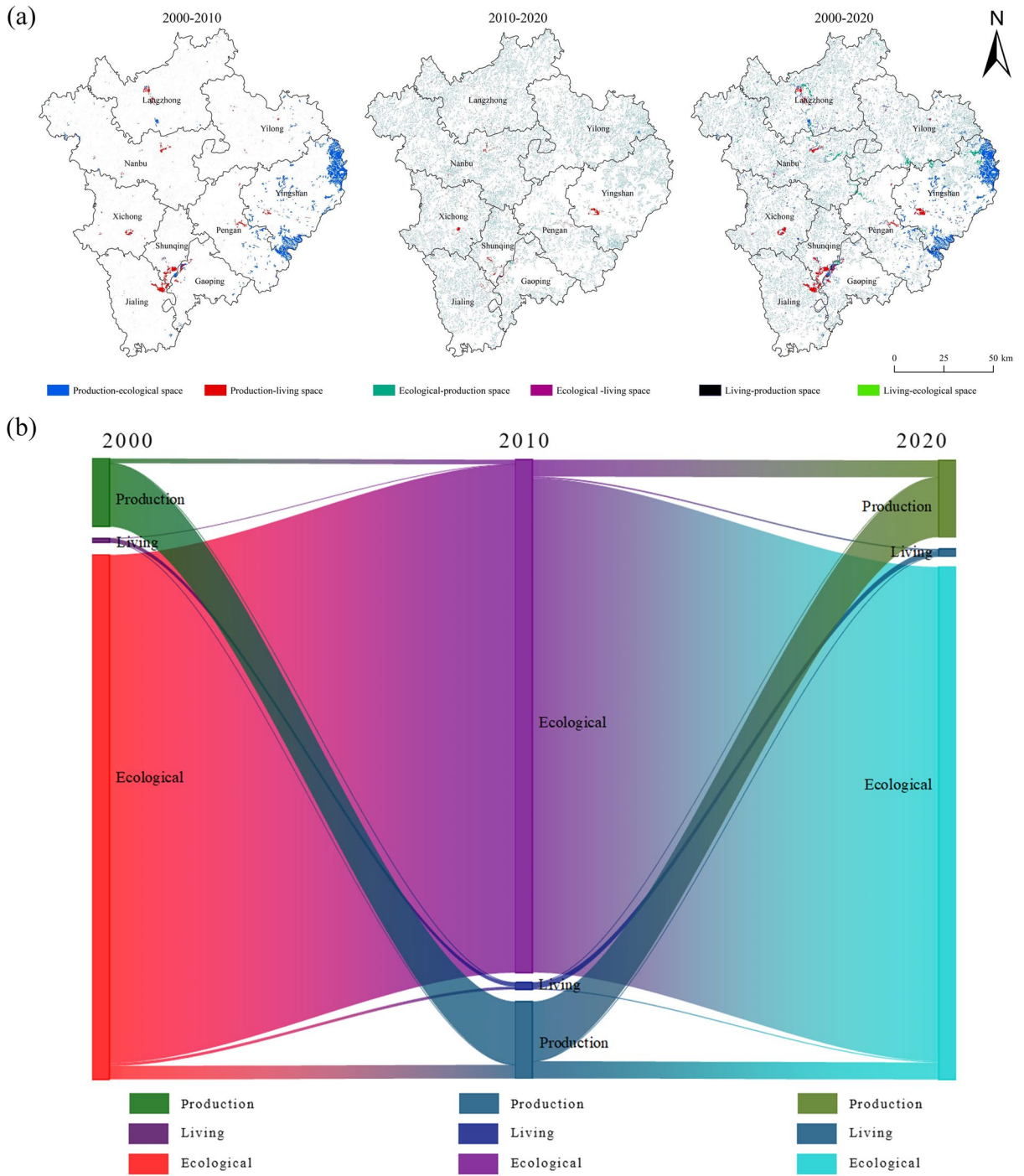
(a)

2000-2010   2010-2020   2000-2020

■ Production-ecological space   ■ Production-living space   ■ Ecological-production space   ■ Ecological -living space   ■ Living-production space   ■ Living-ecological space

(b)

Fig. 4 Spatial-temporal differentiation of PLES in Nanchong City

Table 6 Change of PLES center of gravity coordinates in Nanchong City

Space type		2000	2010	2020
Production space	Longitude (E)	106°15″25″	106°26′05″	106°27′30″
	Latitude (N)	31°13′14″	31°10′35″	31°12′59″
Living space	Longitude (E)	106°06′27″	106°07′05″	106°07′22″
	Latitude (N)	31°13′07″	31°12′20″	31°12′43″
Ecological space	Longitude (E)	106°06′54″	106°06′57″	106°07′03″
	Latitude (N)	31°15′17″	31°15′11″	31°15′07″
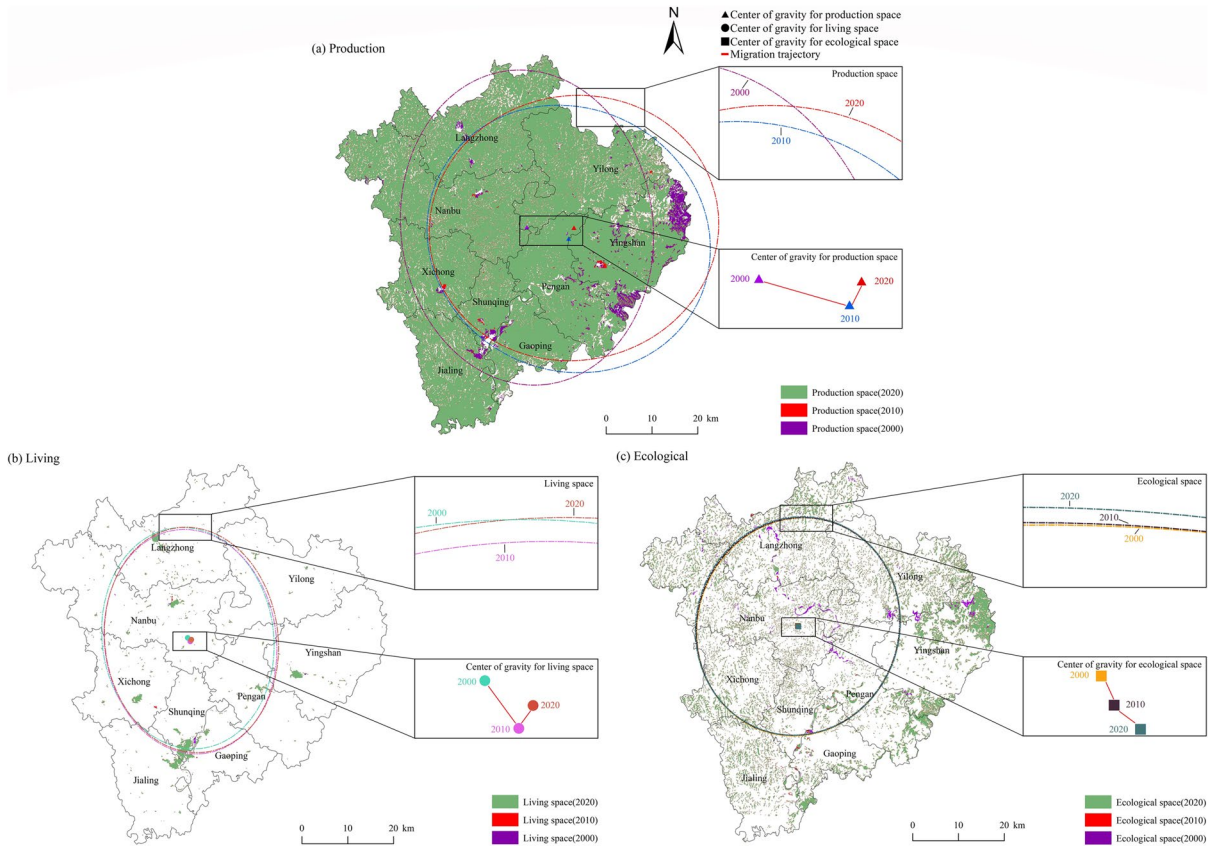
Fig. 5 Changes of standard deviation ellipse and center of gravity of PLES in Nanchong City

northward to Peng'an County, with a total migration of 22.62 km. This movement mainly resulted from the decrease of large areas in Yingshan County over time.

On the other hand, the standard deviation ellipse of the living space in Nanchong City expanded by 141.38km^2 from 2000 to 2020. Both the major and minor axes of the ellipse increased in length, indicating an expansion of the living space in the north-south direction. During the study period, the gravity

center of the living space moved a short distance to the southeast and was situated in Nanbu County, with a total migration of 2.60 km. This migration mainly resulted from the increase of large areas in Shunqing District, Jialing District, and Gaoping District.

Regarding ecological space, the standard deviation ellipse had a south-north distribution, with a slightly increased length of the long axis and a decreased length of the short axis from 2000 to 2020. This change implies that the ecological space

in Nanchong City expanded in the north-south direction. The gravity center of the ecological space was located in Nanbu County, with the smallest cumulative migration distance among the three spaces (0.41 km). Nevertheless, the gravity center shifted slightly to the southeast overall, indicating that the ecological space in Nanchong City grew or decreased relatively uniformly during the study period.
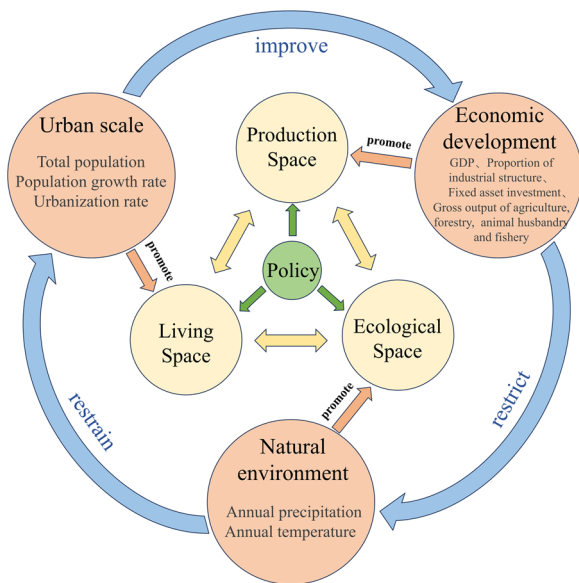

Fig. 6 The influence mechanism of PLES in Nanchong

Driving force of spatial-temporal change of PLES in Nanchong city

In this paper, we hypothesize that the spatial-temporal change of PLES in Nanchong city is the result of the combined effects of urban scale, economic development, natural environment and policies, and that the policy factors act as a "harmonizer" to alleviate the conflicts among spatial types (Fig. 6). In order to test this hypothesis, principal component analysis is used to quantify the influence of each factor on PLES. However, since policy factors cannot be quantified, they are discussed by listing the national policies of the last 20 years.

Driving factors of PLES in Nanchong city

The spatial-temporal change process of PLES in Nanchong is complex. By combining the research results of their influencing factors, an evaluation index system was constructed by selecting 11 driving factors from three aspects including urban scale, economic development, and the natural environment (Table 7). This enabled a quantitative investigation into the primary factors influencing the transformation of PLES categories in Nanchong City. Initially, the raw data underwent standardization, followed by factor analysis. The test results revealed that all values met i the threshold for the single test with KMO = 0.724, Sig = 0.000, confirming the satisfiability of the factor analysis prerequisites for the selected samples.

Table 7 Production-living-ecological space driving force indicators

| Category	Indicating factors	Unit	Serial number
Urban scale	Total population	10,000 people	X1
	Population growth rate	%	X2
	Urbanization rate	%	X3
Economic development	GDP	100 million (current CNY)	X4
	Proportion of primary industry	%	X5
	Proportion of secondary industry	%	X6
	Proportion of tertiary industry	%	X7
	Fixed asset investment	100 million (current CNY)	X8
	Gross output of agriculture, forestry, animal husbandry and fishery	100 million (current CNY)	X9
Natural environment	Annual precipitation	mm	X10
	Annual temperature	°C	X11
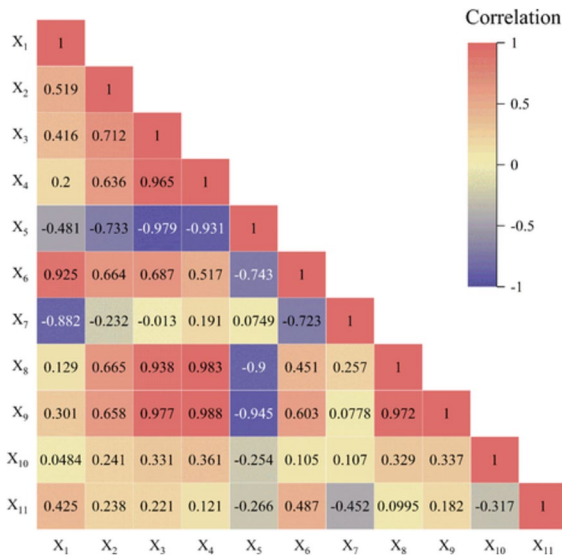
Fig. 7 Correlation coefficient matrix

Table 8 The eigenvalue and cumulative proportion of principal components

Component	Eigenvalue	Percentage of variance	Cumulative contribution rate (%)
1	6.257	56.881	56.881
2	2.712	24.651	81.532
3	1.075	9.771	91.302
4	0.473	4.301	95.604
5	0.380	3.450	99.054
6	0.066	0.600	99.654
7	0.019	0.176	99.830
8	0.010	0.086	99.916
9	0.007	0.062	99.978
10	0.002	0.022	100.000
11	0.000	0.000	100.000

Figure 7 shows that the correlation matrix reveals the degree of correlation among the factors, with greater values indicating higher correlations

Quantitative analysis of PLES driving force in Nanchong city

Table 8 presents the outcomes of principal component analysis conducted on the driving factors over the past 20 years. The analysis identified three primary components, each with an eigenvalue of 6.257, 2.712, and 1.075, respectively. These components accounted for 56.881%, 24.651%, and 9.771% of the total variance, respectively. Together, they accounted for 91.302% of total variance, indicating that the first three components suffice to capture changes across all 11 original factors.

Table 9 shows the principal component load matrix, which was obtained using the formula for calculating principal component loading.

The study results reveal that the determining factors with the highest correlation to the first principal component (F1) include the proportion of primary industry (X5), urbanization rate (X3), gross output of agriculture, forestry, animal husbandry and fishery (X9), GDP (X4), and fixed asset investment (X8). Specifically, X5 negatively correlates with F1, while the other variables have a positive correlation. This finding indicates that F1 primarily reflects economic development-related factors, making it a crucial determinant for the urban expansion of the study area. The second principal component (F2) has higher loading factors of the proportion of tertiary industry (X7) and the total population (X1), with respective coefficients of 0.943 and −0.775. This indicates that F2 mainly represents economic and population factors that are relevant to urban development in the examined region.

The annual precipitation (X10) and the annual temperature (X11) are significantly correlated with the third principal component (F3). These natural environmental factors represent the key factors of F3. Therefore, the primary factors driving the spatiotemporal pattern evolution of PLES in Nanchong from 2000 to 2020 can be categorized into three groups, including economic development factors, urban scale factors, and natural environmental factors.

The linear combinations of the factor scores F1, F2, and F3, and the linear combination of the comprehensive score F, are obtained using the coefficients of the three principal components. These linear combinations are provided below:

$$F_1 = 0.223X_1 + 0.321X_2 + 0.390X_3 + 0.366X_4 - 0.390X_5 \\ + 0.320X_6 - 0.074X_7 + 0.355X_8 + 0.378X_9 \\ + 0.129X_{10} + 0.125X_{11}$$

$$F_2 = -0.471X_1 - 0.064X_2 + 0.101X_3 + 0.227X_4 - 0.049X_5 \\ - 0.350X_6 + 0.573X_7 + 0.259X_8 + 0.163X_9 \\ + 0.213X_{10} - 0.347X_{11}$$

Table 9 The principal component load matrix

Serial number	Indicating factors	F1	F2	F3
X5	Proportion of primary industry	−0.976	−0.081	0.080
X3	Urbanization rate	0.975	0.167	−0.046
X9	Gross output of agriculture, forestry, animal husbandry and fishery	0.946	0.269	−0.082
X4	GDP	0.915	0.374	−0.089
X8	Fixed asset investment	0.888	0.426	−0.130
X2	Population growth rate	0.803	−0.105	0.087
X6	Proportion of secondary industry	0.800	−0.577	0.097
X7	Proportion of tertiary industry	−0.185	0.943	−0.227
X1	Total population	0.557	−0.775	0.240
X10	Annual precipitation	0.313	−0.572	−0.559
X11	Annual temperature	0.323	0.351	0.772
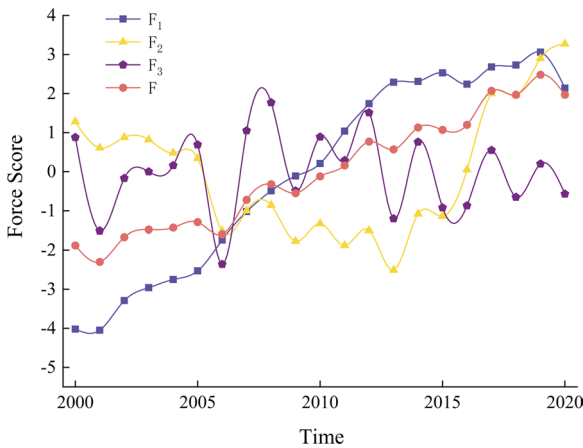
Fig. 8 Trend of driving force scores in Nanchong

$$F_3 = 0.231X_1 + 0.084X_2 - 0.044X_3 - 0.086X_4$$
$$+ 0.077X_5 + 0.094X_6 - 0.219X_7 - 0.125X_8$$
$$- 0.079X_9 + 0.745X_{10} - 0.539X_{11}$$

$$F = 0.569F_1 + 0.247F_2 + 0.098F_3$$

Figure 8 shows the trend of driving force scores for Nanchong's economic development obtained by calculating the factor score equation and comprehensive score equation. These scores continued to rise from 2000 to 2020. Prior to 2010, the driving force score was negative due to the unreasonable economic development structure of Nanchong, leading to a limited impact in PLES. However, after 2010, the score turned positive and had a year-on-year increase,

highlighting the significant impact of a more rational economic structure on the changes of PLES.

The driving force that determines the city scale score exhibits an initial gradual decrease followed by a rapid increase. This trend has a "strong-weak-strong" effect on changes in PLES. Nanchong City's population gradually grew from 7.09 million in 2000 to 7.59 million in 2013, achieving its highest point. However, it swiftly declined to 7.193 million in 2020. The trend of the score is consistent with the fluctuations in population size in Nanchong City. The score was at its lowest point when Nanchong City's population peaked in 2013. This suggests a correlation between population and city scale changes, which exert a certain influence on the spatial-temporal pattern of PLES.

The driving force score related to the natural environment fluctuates around zero in the comprehensive score. Additionally, the coefficient corresponding to the natural environment is merely 0.098. This indicates that the natural environmental factors also contribute to the spatial-temporal changes observed in the PLES. This impact is comparatively weaker than the other two types of driving forces. There is a positive correlation between the three types of driving forces and the comprehensive score. The strongest impact on the comprehensive score is by economic development factors, followed by urban scale factors, whereas natural environment factors have the weakest impact. Therefore, the spatiotemporal pattern evolution of the PLES in Nanchong City is a product of the interconnected influences of economic development, urban scale, and natural environmental factors.

Urban scale factors are a critical driver in spatial-temporal changes in the PLES. Parameters such as population size, population growth rate, and urbanization rate exert substantial influence on land use patterns. During the previous two decades, Nanchong City's population increased from 7.092 million to 7.59 million before dropping rapidly to 7.193 million. Concurrently, the urbanization rate has steadily risen from 20.2 to 35.91%. The expansion of living space initially displayed a swift growth trend that gradually declined, primarily resulting from the transformation of production space to living space. The principal reason behind this trend is the rapid growth of the urban population, resulting in a substantial demand for housing, which in turn encouraged a continuous expansion of living space and the encroachment of other land types. The first decade was characterized by this trend in particular. Consequently, there is a positive correlation between the rate of living space expansion and the level of urbanization. However, a quick decline in population during the last decade hindered the development rate of living space, leading to the spatial-temporal pattern changes within the PLES.

The evolution of the PLES in Nanchong City is primarily shaped by economic development factors. In the last two decades, Nanchong City's GDP has consistently increased, while the proportion of primary industry has been declining. In contrast, the proportion of secondary and tertiary industry experienced a significant surge, rising from 60.2 to 80.8%. While the growing demand for living and ecological spaces puts pressure on production space, but Nanchong City's agricultural output value remained steady. There has been a greater shift towards utilizing production space in Yilong County, Yingshan County, the regions close to the Jialing River Basin, and the Yilong River. The new economic paradigm is driving a shift towards an intensive and efficient utilization of Nanchong City's production space, which was reflected in the increasing participation of industrial parks, complexes, and commercial areas in the city's spatial layout and construction. Yilong and Yingshan County significantly enhanced their production space efficiency, resulting in an improvement in ecological space in Yingshan County and an enhanced living function in the districts of Shunqing, Jialing, and Gaoping. The primary driving force behind these changes is still economic development.

The evolution of the spatial-temporal patterns is significantly shaped by natural environmental factors. The significant influence of natural environmental factors on land use is due to their role in determining the material basis for different uses, leading to the shaping of the initial distribution of population. The significant historical inheritance and inertia of regional economic differences stemming from geographic variations in natural environments is evident. The development of productivity and shifts in production layout evolve continuously in parallel. Hence, the impact of urban scale and economic development factors overrides that of natural environmental factors in shaping the spatiotemporal evolution of the PLES pattern.

Discussion

In recent years, PLES emerged as a prominent and widely discussed topic. Concepts and principles associated with PLES are frequently featured in government work reports and policy documents (Xu et al., 2015). National policies play a crucial role in shaping territorial spatial planning and urban development, thereby exerting a decisive influence on the PLES framework. The implementation of these policies yielded enduring impacts on Nanchong City's PLES dynamics. However, the quantification of policy factors' influence on PLES remains a challenging task. To address this issue, a meticulous analysis was conducted for a period of nearly two decades, with a specific focus on a selection of pertinent policies, each considered within a 5-year timeframe. By adopting this comprehensive approach, we can elucidate the nuanced and lasting effects of national policies on the PLES paradigm in Nanchong City (Fig. 9).

A comprehensive set of policy measures that were implemented by the national government has been playing a pivotal role in fostering economic development and driving the transformation and upgrading of industries in Nanchong City, with a particular emphasis on the realm of production space (Zhou et al., 2017). Notably, the government introduced policies that aimed at invigorating innovation and entrepreneurship, thereby providing robust support and incentives to cultivate a favorable ecosystem for pioneering enterprises. Consequently, these initiatives catalyzed advancements in technological innovation and overall
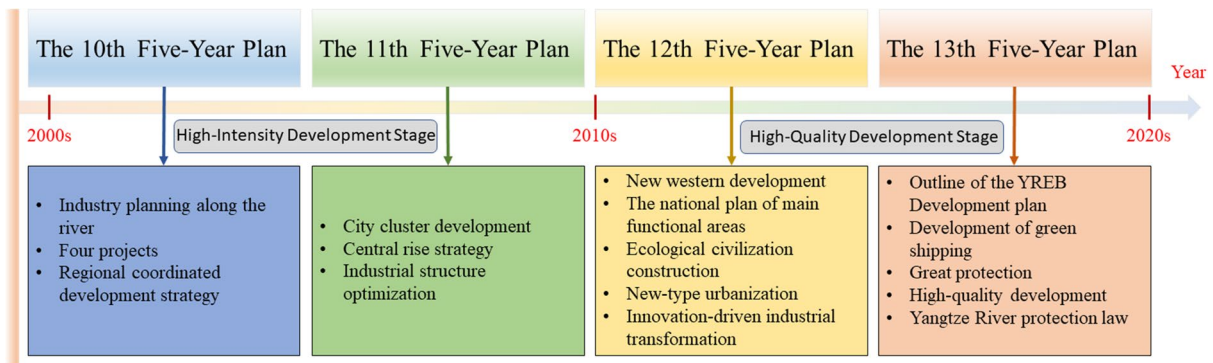
Fig. 9 Relevant national policies of Nanchong City

industrial upgrading within the region. Furthermore, the government made substantial investments in infrastructure development, resulting in notable enhancements in the transportation and logistics capabilities of Nanchong City. As a result, conducive conditions were created to facilitate the growth and prosperity of businesses operating in the area. It is worth underscoring that while there has been a decline in the overall extent of production space, primarily attributable to the reduction of agricultural land (Shan et al., 2017), the expansion of construction land signifies the unwavering endorsement provided by national policies in promoting the efficient utilization of production space and propelling rapid economic growth (Liu & Li, 2017).

Regarding living space, national policies played a constructive role. During this period, the government, as significantly augmented investments in fundamental public service, facilities encompassing education, healthcare, and culture. The introduction of a comprehensive suite of measures elevated the quality of life and welfare of Nanchong City residents (Li et al., 2015; Yep & Forrest, 2016). For instance, increased investment in educational resources has raised educational standards, fostered talent development, and optimized human capital, thereby facilitating societal progress. Additionally, the implementation of healthcare reform policies bolstered healthcare coverage, ensuring the physical well-being of the populace. These policy initiatives provided expanded opportunities and welfare, ultimately enhancing the living standards of Nanchong City residents.

However, national policies also engendered certain adverse consequences for ecological space. Because of the economic development, Nanchong City grappled with environmental pollution and resource depletion. The development and production practices of certain traditional industries contributed to a certain degree of environmental degradation within the locality (Jiang, 2017). Despite the implementation of a range of environmental protection measures and policies, such as energy conservation, green initiatives, and land restoration, the ecological environment of Nanchong City continues to be affected at a certain degree.

Hence, in the forthcoming course of development, it is imperative to continually optimize policies that stimulate economic growth and urbanization while concurrently fostering an efficient production, comfortable living, and aesthetically appealing ecological space. Firstly, particular attention must be directed towards the challenge of population aging, which requires the formulation of specific policies aimed at attracting young talent and promoting population growth to advance the process of urbanization. However, paramount consideration must be given to the rationality of land utilization, resource consumption, and environmental preservation to ensure the sustainability of urban development (Saarikoski et al., 2013). Secondly, a greater emphasis should be placed on providing substantial support for industrial restructuring and driving innovation to promote the development of the tertiary sector and enhance the quality and effectiveness of economic growth (Tian, 2015). Simultaneously, prudent planning and management of financial resources are essential to mitigate the risks associated with excessive

speculation and resource wastage. Lastly, it is crucial to strengthen environmental protection and implement measures for sustainable development, particularly in response to climate change and extreme weather events, by adopting appropriate adaptation and mitigation strategies.

Most of the existing research in this field primarily focus on the more developed regions in the central and eastern parts of China (Liu et al., 2018), as well as the northwest region (Li & Wu, 2022). These studies tend to concentrate on well-developed cities and metropolitan areas, which have undergone rapid urbanization and received substantial financial investments. In contrast, the underdeveloped southwestern regions, such as Nanchong City, have received little attention. However, the research methodology employed in this article effectively captures the development patterns and evolving trends of Nanchong City. Moreover, it demonstrates a remarkable consistency with existing research in terms of the spatial expansion of living space, displaying a fragmented expansion pattern, particularly in the convergence zone of the three districts that directly administered by Nanchong City. The main distinction lies in the fact that in the last decade, Nanchong City experienced the expansion of ecological space at the expense of production space. This phenomenon can be attributed to the favorable inclination of national policies towards environmental protection, which emphasize the necessity of ecological development. Notably, Yingshan County has made the most significant contribution to the expansion of ecological space, driven by its ambitious goal of becoming a "provincial garden city." Regarding the factors contributing to spatiotemporal pattern changes, this study utilizes the principal component analysis method, while this approach offers advantages such as feasibility and ease of analysis, compared to the alternative models including GWR, geographically weighted regression, and OLS. It is important to note that it may be less robust in terms of analytical capabilities (Yang et al., 2018). Therefore, future research could benefit from integrating these models to examine the influencing factors, leveraging the strengths of each model. Additionally, when selecting natural factors, incorporating variables such as DEM, slope, and aspect could enhance the research's alignment with objective reality.

Conclusions

In this study, an analysis was conducted to examine the spatiotemporal pattern of changes in the production-living-ecological space (PLES) in Nanchong City from 2000 to 2020. Various analytical methods, including the land use transfer matrix, land use dynamic degree, standard deviation ellipse, gravity center transfer, and principal component analysis, were applied to investigate the underlying factors influencing these changes. The main findings are shown as follows:

(1) Between 2000 and 2020, Nanchong City underwent a decline in the extent of production space, accompanied by notable growth in both living space and ecological space areas. The production areas in the south and northeast of Yingshan County witnessed the greatest transfer to ecological space. The living space showed significant levels of dynamism and rapidly expanded outward from the central intersection of the three core districts. The Jialing and Yilong Rivers helped facilitate the development of production areas due to their proximity to water sources. Nanchong City's PLES transformation was influenced by numerous factors, including urbanization rates, national policies, and natural surroundings. The process of spatiotemporal pattern evolution often includes an array of interrelated and interacting factors, making it a complex phenomenon.

(2) In the past two decades, there was consistent expansion and relocation of production, living, and ecological spaces in Nanchong City. The production space expanded in an east-west trend, with a center of gravity that migrated south-east from Yilong County to Peng'an County, covering a migration distance of 22.62 km. As for the living space and ecological space, they have been expanding in the north-south direction. The center of gravity for both is in Nanbu County and then migrated towards the southeast. However, the center of gravity for living space has migrated slightly further compared to that of the ecological space. The trends indicate that urbanization and population growth in Nanchong resulted in the expansion and development of various spatial domains.

(3) The evolution of the PLES in Nanchong City is closely linked to factors such as population growth, economic development, and natural environment. These factors often interact in complex ways during the process of conversion between PLES classes. The evolution of the PLES is primarily driven by economic development, followed by the urban scale factor. The influence of natural environment factors on the PLES is relatively weak. Therefore, it can be concluded that the spatial-temporal changes in the PLES are the result of the combined effects of economic development, urban scale, and the natural environment.

Data availability   The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval   Not applicable.

Consent to participate   Not applicable.

Consent for publication   Not applicable.

Competing interests   The authors declare no competing interests.

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