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Spatiotemporal evolution and Sustainably comprehensive zoning optimization of production–living–ecological functions in the Mountain–Flatland areas

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A R T I C L E I N F O

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A B S T R A C T

Examining the spatiotemporal changes of territorial space is crucial for addressing the conflict between economic-social development and the natural environment and achieving optimal territorial space utilization. However, there is a research gap regarding the spatial characteristics and optimization in the mountain–flatland area. To address this gap, this paper focuses on the urban agglomeration in Central Yunnan (UACY) as a representative mountain-flatland area. A mountain–flatland classification model was established. Based on the evaluation of production–living– ecological functions, the economic models were introduced to measure the balance degree, and further researched the spatiotemporal evolution and coupling coordination characteristics by spatial analysis from 2010 to 2020. The findings indicate the following: (1) The study area exhibited distinct mountain-flatland differentiation, with "western mountainous counties (MCs)/semi-mountainous and semi-flatland counties (SMSFCs), central flatland counties (FCs), and eastern SMSFCs". production function (PF) primarily formed a cluster in the central-northeastern areas of FCs and of SMSFCs, living function (LF) was highly clustered in the central areas of FCs, remained stable, and ecological function (EF) was significantly clustered in the northwestern regions of MCs and of SMSFCs, significantly enhanced in the northeast. (2) The imbalance degree followed the order LF > PF > EF, showing a decreasing trend primarily driven by intra-group imbalances within FCs, SMSFCs, and MCs. The coordinate areas were mainly concentrated in central FCs, and the dysfunctional areas was largely located in MCs and SMSFCs, the degree was improved, especially in northwestern and southeastern MCs and SMSFCs. (3) The study area fell into 18 functional areas, optimized into 13 areas, with recommendations for differentiated development control paths to achieve an optimization of PLEFs. These results provide theoretical references for promoting sustainable utilization of territorial resources and facilitating high-quality regional development in UACY and other parts of the country.

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1. Introduction

The implementation of reform and opening up has had a continuous effect on the sustainable conservation and utilization of resources [1]. This effect can be attributed to the ongoing high-speed social and economic development, the steady and rapid growth urbanization, and the continuous improvement of production levels and living standards. To achieve environmentally friendly socio-economic development and ecological civilization, the 19th National Congress of the CPC Central Committee made a significant judgment on China's economic development, "shifting from a stage of high-speed growth to a stage of high-quality development" [2]. Promoting high-quality economic development has become a crucial strategy for China's development in the new era, necessitating the establishment of a territorial spatial planning system to provide spatial support for high-quality development [3]. The territorial space can be classified into production space, living space, and ecological space based on their respective functions. The report of the 18th National Congress of the CPC Central Committee emphasizes the need for "intensive and efficient production space, livable and moderate living space, and beautiful mountain and clear water in ecological space" as the objectives to quantify the spatial functions of the country, aiming at achieving an optimized pattern of territorial spatial development [4,5]. This approach guides the optimization of the PLEF. As the foundation for human survival and development as well as social and economic activities, the territorial space plays a pivotal role in production function (PF), living function (LF), and ecological function (EF) [6]. The production– living– ecological function (PLEF) encompasses activities such as land-based production, material and spiritual life security for residents, material and energy flow and ecological environment regulation, and so forth. It is a multifunctional product that integrates the elements of the land, economy, energy, and ecology systems. Reasonably identifying the functions of territorial space and understanding its evolutionary characteristics is of great theoretical and practical significance, which lays a basis for optimizing the layout of the territorial space and the rational development and utilization of resources. The research on FLEF has yielded fruitful results [7]. Scholars have primarily focused on identifying the functions of the production–living–ecological spaces [8], spatial structure evaluation [9], formation mechanism detection [10], spatial and temporal evolution characteristics [11], spatial simulation and optimization [12], interrelationships [13], among other areas of investigation.

The identification of the PLEF serves as the foundation for studying territorial space. Qualitative identification of land use type evaluation [14] and quantitative measurement of the index system [15] are the main methods to identify the PLEF. The former generally delineates the trituration space by subsuming land use types or assigning values to different land classes, usually at the raster scale, and the latter conforms to system science and spatial function theory [16], using economic and social, resource conservation and utilization data, taking into account the stability and accessibility of indicators [17], the evaluation index system is constructed hierarchically, and the evaluation unit is usually an administrative district [18]. The PLEF generally encompasses two modes, including single function and composite function. Specifically, single function represents the PF, LF and EF, while composite function refers to the evaluation unit that contains more than two functions, scholars comprehensively determine the type of dominant function and add composite types such as production-life function and production-ecological function through methods such as comparative advantage index and primacy index [7].

Based on different scales [17], various methods have been employed to analyze the spatial and temporal change characteristics of the PLEF, guiding land use, sustainable development, resource optimization, ecological environmental protection and sustainable urban assessment, these methods include land use dynamic attitude [18], transfer matrix [19], geological information mapping [20], standard deviation ellipse [21], center of gravity offset [22], spatial correlation [23], landscape pattern index [4], bivariate local Moran's I model, as well as the coupled coordination degree model, etc. The study covers various scales, ranging from national [6] and watershed levels [24] to provincial [25], urban cluster [26], metropolitan area [27], city [28], county [29], township [30], and administrative village levels [31]. The primary focus lies on the provincial, city, county, and village levels [7]. The equilibrium of PF, LF, and EF represents a state of maintaining mutual coordination and balance among functions in socio-economic development. The coupling coordination degree (CCD) is the level of interdependence and association between systems, and the coupling coordination model is usually applied to two or more subsystems, such as population and land, urbanization city-industry integration [32], economy–resource–environment-ecosystem [33]. The interdependence and mutual constraints between PF, LF, and EF, to realize the goal of sustainable development, need to achieve the synergistic development of pelf through a variety of means and strategies, and to achieve the Coordination and balance among PF, LF, EF is the prerequisite and guarantee of spatial synergistic utilization. The CCD model has been extensively employed to measure the coupling and coordination relationship among land functions and assess the coupling and coordination relationship among PF, LF, and EF [34].

Territorial functional zoning holds significant importance in facilitating the rational use of land resources, safeguarding the ecological environment, and achieving the coordinated development of urban and rural areas. Previous research has predominantly employed two methods: spatial superposition method or spatial clustering algorithm. These methods rely on the functional measurement of territorial functions [13,34] and correlation evaluation [11], symbiotic relationship [12], spatial heterogeneity [35], and carrying capacity [31]. By considering the functional value, clustering patterns, and various evaluation criteria, these methods effectively outline distinct zoning control programs.

China is renowned for its vast expanse of mountainous regions, which encompass plateaus and hills, taking up over 60 % of the national land area [35]. It is important to coordinate the synergistic protection and development between mountainous and flatland areas to achieve efficient protection and utilization of the territorial space [36]. Existing studies have only analyzed the spatial and temporal change characteristics [37], land use evolution characteristics [38], and Suitability of human settlements [39], based on the characteristics of Mountain-Flatland.

Scholars have carried out considerable studies at different levels, whereas there are still some deficiencies. In the identification of the PLEF, it is usually ignored the multifunctional attributes of the national territory space, the spatial and temporal evolution of the

PLEF is dominated by the evolution law of the local area, the balanced nature of the overall functions of the study area has not been evaluated, and the integrated zoning of the national territory does not consider the degree of coupling and coordination to achieve sustainable development, and the connectivity and the integrity of the intra-region are insufficient. Numerous questions remain unanswered, such as potential variations in the distribution of different functions between mountainous and flatland areas, the balance or imbalance of the distribution of the three functions, the underlying reasons for such balance or imbalance, potential disparities between mountains and flatlands, and whether the clustering and integration of functions within urban clusters, as well as their spatial and temporal differentiations, are dependent on mountain-flatland dynamics. Furthermore, the functional zoning has not been thoroughly investigated, disregarding natural geographic patterns, especially the distinct characteristics of mountains and flatlands.

The UACY region, situated in central Yunnan province, holds significant strategic importance as a key node of the "One Belt, One Road" initiative and serves as a radiation center for South and Southeast Asia. This region exhibits characteristics such as high population density, extensive land development, concentrated distribution of arable land, fragile ecological environment, and the prominent conflicts between economic development, farmland protection and ecological protection. Moreover, the region features an intricate combination of mountains, dams, and deep valleys, representing a typical area with distinct mountain and dam characteristics. In light of these factors, the UACY region has been selected as the study area for this paper. The objectives of this paper are as follows: (1) to build the mountain-flatland model, and divide the study area into different types of mountain-flatland; (2) to quantitatively identify the spatial functions of the national territory based on the perspective of the PLEF; (3) to analyze the characteristics of change and the degree of balance of the overall distribution of PLEF and the spatial and temporal evolution characteristics of the PLEF within the study area; (4) to comprehensively classify the functional areas of the national territory and propose the optimization strategies for a wide range of areas.

2. Materials and methods

2.1. Study area

The UACY is situated in central Yunnan Province, located between 100°43′ and 104°49′ east longitude from 23°01′ to 27°04′ north latitude in southwest China. It takes up a land area of approximately 111,400 km^2, which encompasses Kunming City, Qujing City, Yuxi City, Chuxiong Yi Autonomous Prefecture, and seven counties (cities) in the northern part of Honghe Hani and Yi Autonomous Prefecture, consisting of a total of 49 counties (cities and districts), as depicted in Fig. 1. As of the end of 2020, the resident population reached 21.96 million, with a GDP of 150.74 billion yuan. The UACY region holds significant prominence as one of the 19 urban agglomerations in the country, serving as the economic, political, and cultural center of Yunnan Province. Moreover, it plays a crucial role in food production and ecological protection within the province. The predominant land use types are woodland and arable land,

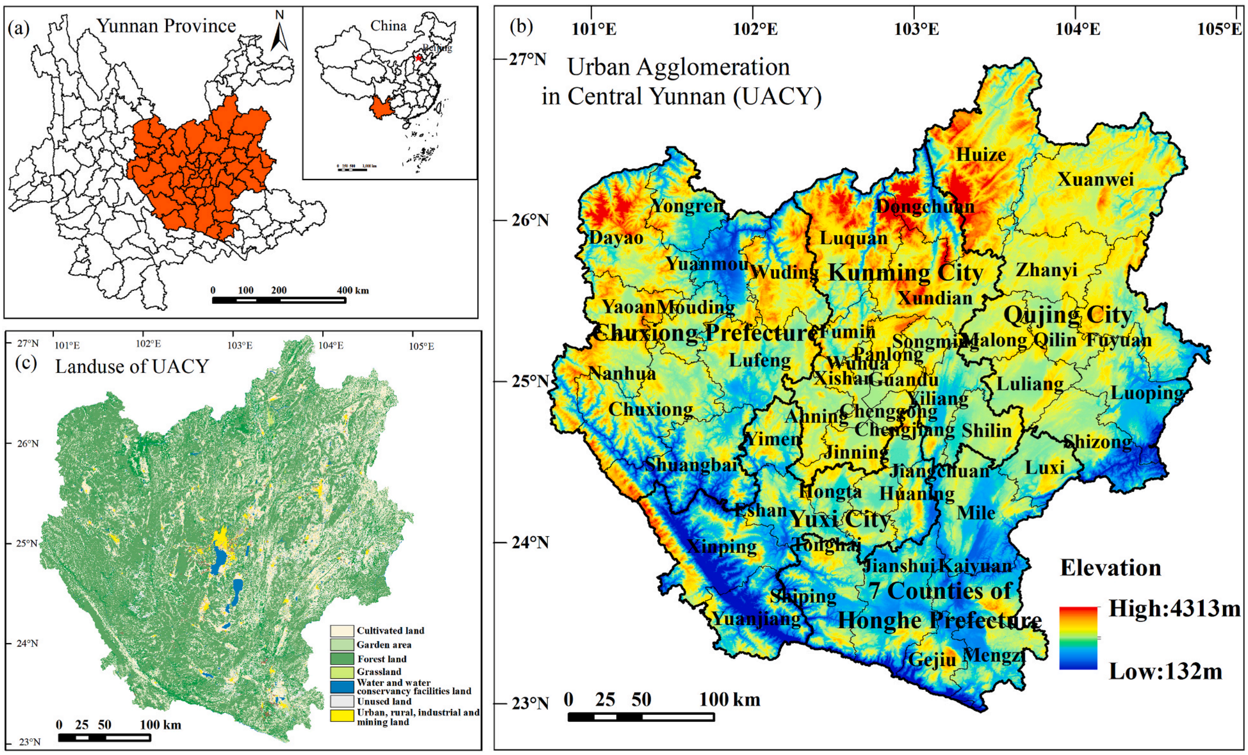

Fig. 1. Location of study area.

accounting for 32.8 % of Yunnan Province's national land area, 40.42 % of the province's arable land, and 45 % of the construction land. With an altitude of 312~4313 m and a relative height difference of 4001 m, more than 80 % of the land in the whole area is characterized by mountainous and hilly terrain. This area represents a typical mountain-flatland interlocking region, exhibiting substantial discrepancies in natural resource endowment and in economic and social development between the flatland and mountainous areas. Consequently, it faces significant challenges in the protection, development, and utilization of land space. Given these distinctive characteristics, analyzing the spatial pattern and evolutionary traits of the national territory becomes pivotal in understanding and addressing the complexities associated with the mountain and flatland dynamics.

2.2. Data sources

The primary data utilized in this paper comprise various datasets related to socioeconomic data, land use data, administrative district boundaries for the years 2010 and 2020. These datasets include socioeconomic data from the *Yunnan Provincial Statistical Yearbook*, *China County Statistical Yearbook*, the relevant prefecture (city) *National Economic and Social Development Statistical Bulletin*. Additionally, land use data is sourced from the Yunnan Provincial Land Use Annual Change Survey database. The administrative divisions and names used in this paper are based on the information as of the end of 2020. Table 1 provides a comprehensive overview of the data sources employed in this paper.

2.3. Research ideas

Territorial space is a complex entity shaped by the interplay of various factors, encompassing production function (PF), living function (LF), and ecological function (EF). These functions are interconnected, exerting mutual influences and experiencing constraints or promotional effects. PFs primarily encompass agricultural production, industrial production, and tertiary sector activities, while LFs include residence, work, social security, and recreation. EFs pertain to the maintenance and regulation of biodiversity and ecological balance. The three functions are interdependent, with EF providing resources for PF and LF, and changes in EF restricting LF and PF. The PF contributes to the improvement of ecological and LFs through technical and financial means, but can also lead to environmental pollution and biological damage, affecting ecological balance and biodiversity. Similarly, environmental pollution caused by the PF influences both ecological and LFs. The LF relies on good production and EF to ensure the survival and development of human beings. Overall, the three functions exhibit a relationship of mutual constraint or promotion (Fig. 2).

The optimal state of the function of territorial space is achieved through balanced coordination of PF, LF, and EF. Only by attaining the coordination of the three can the maximum potential of territorial space be realized, thus promoting the high-quality development of territorial space. However, the PF, LF, EF are influenced by natural geographical conditions, especially the topographic and geomorphological features. Therefore, it is crucial to investigate the association between the PLE spaces and the evolution of the law under the characteristics of different mountain dams. This exploration facilitates the rational allocation of PLEF in such areas, facilitating sustainable development.

This paper focuses on the county as the research unit. Firstly, it delineates the types of mountains and dams by constructing the mountain-flatland comprehensive evaluation index, thus laying a foundation for studying the spatial evolution and zoning of the PLEF. An evaluation system of the PLEF is constructed to quantitatively identify the PLEF. The distribution and evolution of PLEF are analyzed from the overall study area to its interior. Furthermore, the distribution and evolution of the three functions are identified, and the functional balance of the entire study area is evaluated. Next, the spatial and temporal evolution of the three functions from the interior is explored. (3) Finally, the functional zoning in the context of mountain dams is determined comprehensively through the coupling coordination degree and comparative advantage index, and optimization recommendations are proposed.

In this paper, the urban agglomeration in Central Yunnan (UACY) region, with its typical mountain and flatland features, serves as a case study. Based on data from 2010 to 2020 and adopting the PLEF perspective, an evaluation index system is established to identify territorial spatial functions at the county level. The mountain and flatland types of the counties are determined using a comprehensive

Table 1
Data sources in this study.

Data Aspect	Data Content	Time	Data Source	Data Declaration
Social economy	GDP, Population, Production, etc.	2010, 2020	http://stats.yn.gov.cn/	Administrative district statistics
Environment	Air quality, Sewage discharge, etc. ecological protection red line	2010, 2020	http://stats.yn.gov.cn/, https://www.yn.gov.cn/sjfb/ Yunnan Provincial Department of Natural Resources	Administrative district statistics Vector (Shapefile Format)
Land use	Arable land, woodland, city, town, village, etc.	2010, 2020	Yunnan Provincial Land Use Survey database	Vector (Shapefile Format)
Administrative district	Administrative district boundary	2020	http://www.resdc.cn/	Vector (Shapefile Format)
Flatland	Flatland boundary	2014	Yunnan Provincial Land Use Survey database	Vector (Shapefile Format)
Terrain	DEM	2010, 2020	http://www.resdc.cn/	Raster (30 m Grid)

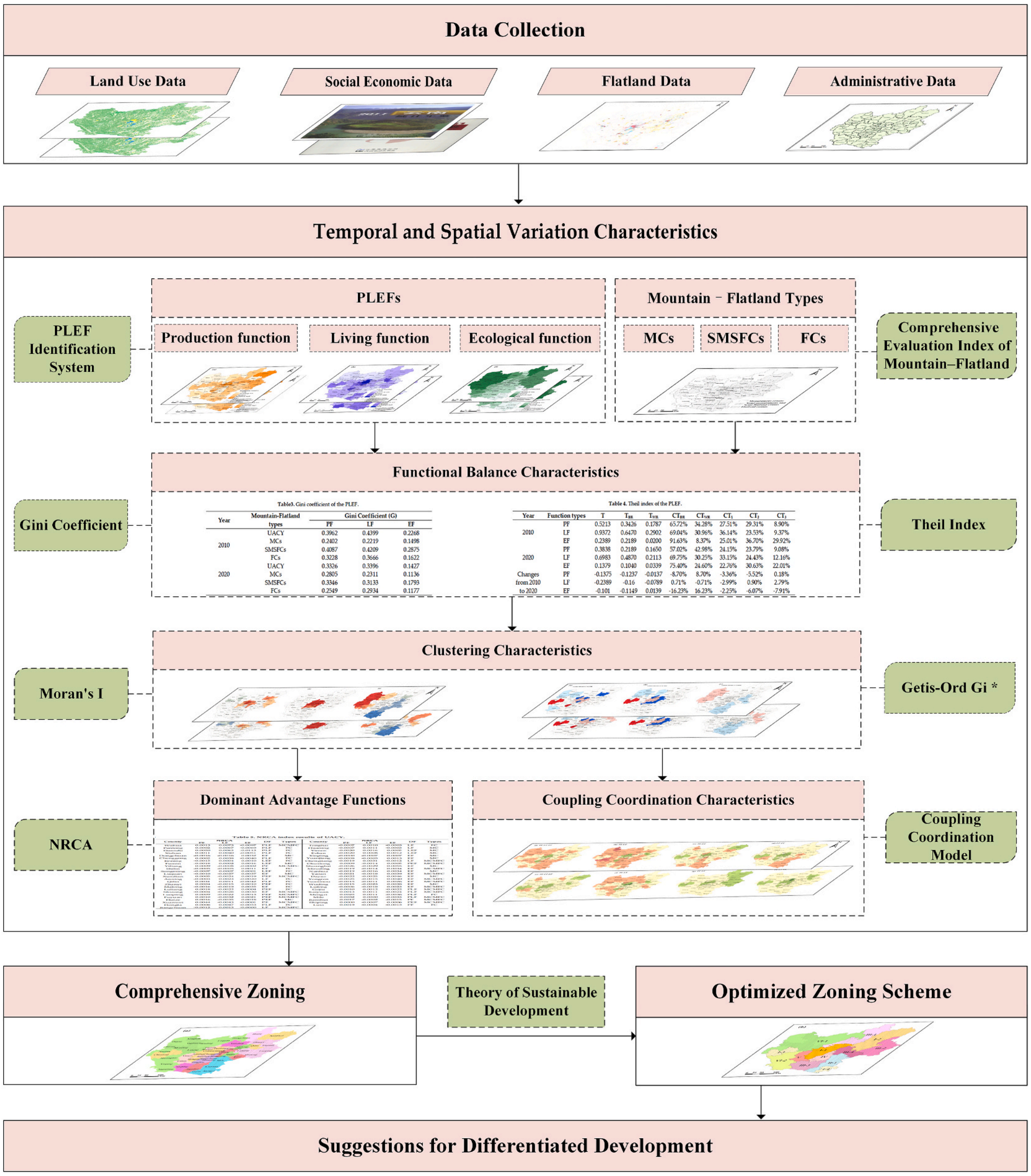

Fig. 2. The conceptual classification framework of territorial space function.

evaluation index, and various models are employed to analyze the differentiation and evolution characteristics of PLEF on an overall and interrelated level. Functional zoning is then determined based on coordination and comparative advantages (Fig. 3).

2.4. Methods

2.4.1. Comprehensive evaluation index of Mountain–Flatland

According to the rules for the Implementation of the Second National Land Survey of Yunnan Province, "flatland" refers to mountain basins, valleys, and other flat areas with slope of not less than 8° and contiguous area of not less than 1 km^2. According to the results of the survey, the flatlands, accounting for 6 % of the national land area. Based on previous studies [40], we considered that the territory can fall into different types of flatland-mountain by county unit, with the following calculation Eq. (1):

$$FI = \frac{A_b}{At} \times \alpha_1 + \frac{N_b}{Nt} \times \alpha_2 \tag{1}$$

where *FI* represents Comprehensive Evaluation Index of Mountain–Flatland, A_b is the area of a county's flatland area, A_t is the area of

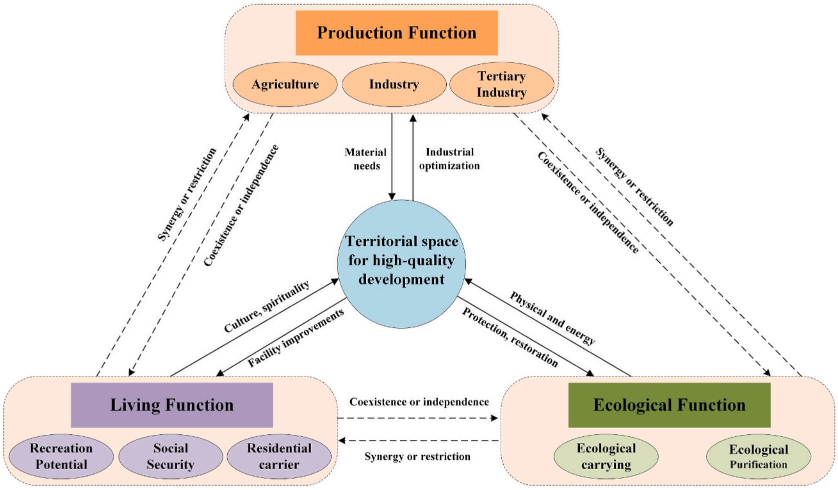

Fig. 3. Research framework.

the country, N_b is the number of a county single flatland area $\geq$100 km^2, N_t is the number of urban clusters with a single dam area $\geq$100 km^2. The index is divided into 3 levels according to geometric grading from high to low, which are named FCs, SMSFCs, and MCs.

2.4.2. PLEF identification index system

Taking into account the multifunctional properties, spatial variability, and systemic nature of land, the development and current situation of the UACY, county-level administrative districts as the identification unit [16,41,42], and after consulting with experts in land, geography, urban and rural planning, agriculture, and ecology, and taking into account the accessibility of data, 21 indices were selected to build the evaluation index system of the PLEFs in the study area (Table 2). The weights of the indices were determined by the entropy method after dimensionless by the polar method [43]. The value of the PLEF was calculated by Eq. (2).

$$F_a = \sum W_b \times y_{ab} \tag{2}$$

where F_a represents the PLEF index value of the *ath* cell, y_{ab} represents the standardized value of the PLEF evaluation index. W_b is the weight of the *bth* evaluation index. the PLEF values were calculated and divided into high-, relatively high-, medium-, relatively low-, and low-value areas using the natural breakpoint method.

2.4.3. Gini coefficient and Theil Index

The Gini coefficient is derived from economics, serves as a frequently used index of income disparity between residents of a country

Table 2
Multi-function evaluation index system of PLEFs.

Target layer	Guideline layer	Indicator layer	Weights in 2010	Weights in 2020
PF	Agricultural production	Production of major crops	0.0946	0.1038
		Total output value of agriculture, forestry, animal husbandry and fishery	0.0571	0.0647
		Livestock and aquatic products production	0.0961	0.0999
	Non-agricultural production	Output value of secondary and tertiary industries	0.1750	0.1726
		Total retail sales of social consumer goods	0.2214	0.1571
		Fixed asset investment	0.1397	0.1075
	Production conditions	Proportion of transportation land to national land area	0.0687	0.1086
		Arable land area	0.0732	0.0875
		Population	0.0742	0.0984
LF	Standard of living	GDP per capita	0.1771	0.1396
		Total retail sales of social consumer goods per capita	0.2111	0.1307
		Proportion of road land	0.1532	0.1929
	Social Security	Per capita disposable income of rural permanent residents	0.0769	0.0982
		Year-end balance of household deposits	0.3022	0.3541
		Average salary of employees	0.0794	0.0845
EF	Maintenance function	Proportion of total forested grassland wetland area	0.1628	0.1967
		Forest cover	0.0628	0.0958
		Proportion of ecological protection red line area	0.0696	0.0819
	Load-bearing function	Sewage discharge rate	0.2968	0.2823
		Air quality pollution rate	0.0572	0.1177
		General industrial solid waste comprehensive utilization rate	0.3509	0.2256

or region [44,45], and has been extensively employed in geography [46]. In this paper, the Gini coefficient is introduced to quantify the degree of difference in the distribution of the PLEF in the study area, calculated by the following Eq. (3):

$$G = \frac{1}{2n^2\overline{x}} \sum_{i=1}^{n} \sum_{j=1}^{n} |x_i - x_j| \tag{3}$$

where G represents Gini coefficient, n denotes total number of the counties, $\overline{x}$ expresses the average value of a particular PLEF in the study area, x_i, x_j are the values of any two counties PLEFs. It is generally believed that [45,46] the $G < 0.2$ is uniform, $0.2 \leq G < 0.3$ is relatively uniform, $0.3 \leq G < 0.4$, was barely uniform. $G = 0.4$ is the "warning value", $0.4 \leq G < 0.6$, in large differences, $G > 0.6$, is highly unbalanced.

To further check the Gini coefficient and analyze the contribution of the imbalance in different mountain-flatland types,The Theil index is one of the most important indices of regional economic differences, first proposed by Theil in 1967 to measure the difference in income level of a region and now extensively used in the study of regional economic, demographic, and social differences [47,48]. It has good decomposability and can be decomposed into intra-group and inter-group Theil indices when the sample can fall into multiple groups. We use the Theil index and its decomposition idea to build a Theil index for the differences of the PLEFs of urban clusters by grouping MCs, FCs, and SMSFCs, exploring the differences of the PLEFs. The overall spatial and intra-group differences were investigated, and the contribution rate of the group was used to explore the intensity of the effect. The greater the value of the Theil index, the greater the difference between the PLEF and the more unbalanced the PLEFs, while a value of 0 indicates that the PLEFs are evenly distributed in the respective county. Eqs. (4)–(6) are as follows:

$$T = \sum_i \sum_j \left(\frac{Yij}{Y}\right) \ln\left(\frac{Yij/Y}{Nij/N}\right) = \sum_i \left(\frac{Yi}{Y}\right) \sum_j \left(\frac{Yij}{Yi}\right) \ln\left(\frac{Yij/Yi}{Nij/Ni}\right) + \sum_i \frac{Yi}{Y} \ln\left(\frac{Yij/Y}{Nij/N}\right) = TWR + TBR \tag{4}$$

$$Ti = \sum_j \left(\frac{Yij}{Yi}\right) \ln\left(\frac{Yij/Yi}{Nij/Ni}\right) \tag{5}$$

$$CTWR = TWR/_T, CTBR = TBR/_T, CTi = Ti/_T \tag{6}$$

where T represents Theil Index of all counties in study area, T_i denotes regional Thiel index, Y_{ij} expresses the value of PLEF in the county, Y denotes the sum of a PLEF value for all counties, Y_i is the sum of a type counties(MC, FC, and SMSFC) PLEF value, N_{ij} expresses the area of a county, N_j is the area of a type counties(MC, FC, and SMSFC), N is the area of study area, T_{WR}, T_{BR} are the Thiel indexes of inter-group and intra-group of PLEFs, i is the number of groups, in this paper $i = 3$, j is the number of counties, CT_{WR}, CT_{BR} represent the contribution of inter-group and intra-group differences to the overall differences. CT_i is a certain type's contribution of regional differences of city to the overall differences.

2.4.4. Spatial autocorrelation and hotspot analysis

The clustering characteristics of the PLEFs were assessed by using the Global Moran's I, and the significance test should be conducted The value exceeding 0 indicated negative correlation, equal to 0 was no correlation, less than 0 was positive correlation. The correlation degree of the PLEFs in ArcGIS software was classified by using the Local Moran's I index, so as to create LISA maps based on homogeneous and heterogeneous agglomeration areas [24,49]. The spatial functions clustering degrees of the PLEF are classified into five types: high-high cluster (H–H), low-low cluster (L-L), high-low cluster (H-L), low-high cluster (L-H), and non-significant area.

Hotspot analysis can contribute to the spatial clustering situation and the manner of clustering the high or low values of the PLEF. The cold-spot and hotspot area of the PLEF was analyzed by using the Getis-Ord G_i * in ArcGIS software [50], and the cold hotspot partition of the PLEF was performed by Z value and G_i * value [51], the results were divided into seven levels: extremely significant hotspot, significant hotspot, hotspot, insignificant, cold spot, significant cold spot, and extremely significant cold spot.

2.4.5. Coupling coordination model

Coupling degree represents the phenomenon whereby two or more systems or forms of motion influence each other through interaction [34]. The greater the value, the stronger the mutual influence, the Coupling coordination degree (CCD) reflects the degree of coordination between different functions coupled with each other. Based on previous research [52], the CCD was presented to explore whether there was interaction and influence in PF, LF, EF, to deeply explore the level of coupling coordination and the mechanism of action, the spatiotemporal pattern characteristics of the two–two coupling coordination of PF, LF, and EF were further analyzed. The calculation Eqs. (7)–(9) are as follows:

$$C = n \times \left[\frac{F1 \times F2 \times \cdots \times Fn}{(F1 + F2 + \cdots + Fn)}\right]^{\frac{1}{n}} \tag{7}$$

$$T = \chi 1F1 + \chi 2F2 + \cdots + \chi nFn \tag{8}$$

$$D = \sqrt{C \times T} \tag{9}$$

where C expresses the coupling degree, F_n is the PLEF value of the county, T denotes the coordination degree, χ^n is the weight, considered that the PLEFs are equally important, $\chi^n = 1/n$. D represents coupling coordination degree, n is the number, $n = 2$ when analyzing two-two function interactions, and $n = 3$ when analyzing three function interactions. $D\in(0.0,0.2]$ refers to serious imbalance, $D\in(0.2,0.4]$ is moderate imbalance, $D\in(0.4,0.6]$ is basic coordination, $D\in(0.6,0.8]$ is moderate coordination, $D\in(0.8,1.0]$ is high coordination [52].

2.4.6. The revealed comparative advantage index

The normalized revealed comparative advantage index (NRCA), which is not bounded by time and space, offers the advantage of achieving continuous comparison in space and time. Moreover, it is extensively employed in a wide variety of fields [53]. It was applied to the quantitative identification of the dominant function (DF) of the county unit in the study area.

$$NRCA_n^m = X_n^m / X - X_n X^m / XX \tag{10}$$

$NRCA$ represents value of Revealed Comparative Advantage Index, $NRCA>0$ is the dominant function, X_{nm} is the value of a function for a county, X_n is the sum of a functional value for all counties, X_m is the sum of all functional values for a county, X is the sum of all functional values for all counties.

2.4.7. Functional comprehensive zoning

We divided the optimization partition of the territorial space functions of the urban agglomeration in accordance with the characteristics of mountain–flatland, the comparative coupling coordination characteristics of the PLEF, and the comparative advantageous functions in 2020. The specific division method is shown below: To reflect the coordinated development orientation of the three functions, this paper's comprehensive territorial zoning was mainly based on the following principles: (1) the degree of coupling coordination: PF, LF, and EF coupling coordination degree was greater than or equal to the medium degree of coordination area, divided into PF-LF-EF Coordination Area; (2) PF, LF, EF, PF, LF, or LF-EF Coordination Area; (3) the rest of the area coupling coordination degree was below the moderate coordination, the type of area through the comparative advantage index to determine the type of area; (4) all the areas were compounded with the dam feature type to form the final Functional Comprehensive Zoning. Shown in Table 3.

3. Results

3.1. Characteristics of Mountain–Flatland

Fig. 4 depicts the divided mountain and flatland results in the UACY, which was divided into FCs, SMSFCs, MCs by the geometric grading of the comprehensive evaluation index of mountain and flatland. There were 16 FCs, 20 SMSFCs, and 13 MCs, with a general distribution of "western MC/SMSFC- central FC - eastern SMSFC". The FCs were mainly located in Kunming City, Qujing City, and Yuxi City in the central. The SMSFCs were scattered in the Chuxiong Prefecture in the northwestern, eastern Qujing City, and southern Honghe Prefecture, while the MCs were mainly located in the north and southwest, Chuxiong Prefecture, and Honghe Prefecture.

Table 3
Rules of spatial functional zoning.

Mountain–Flatland types			Functional integrated zoning	Coupling coordination degree				NRCA functions
				PF–LF–EF	PF–LF	PF–EF	LF–EF	
MC	FC	SMSFC	PF–LF–EF Coordination Zone	≥moderate coordination	–	–	–	–
			PF–LF Coordination Zone	< moderate coordination	≥moderate coordination	< moderate coordination	< moderate coordination	–
			PF–EF Coordination Zone		< moderate coordination	≥moderate coordination	< moderate coordination	–
			LF–EF Coordination Zone		< moderate coordination	< moderate coordination	≥moderate coordination	–
			PF–LF Advantageous Zone		< moderate coordination	< moderate coordination	< moderate coordination	PF–LF
			PF–EF Advantageous Zone					PF–EF
			LF–EF Advantageous Zone					LF–EF
			PF Advantageous Zone					PF
			LF Advantageous Zone					LF
			EF Advantageous Zone					EF

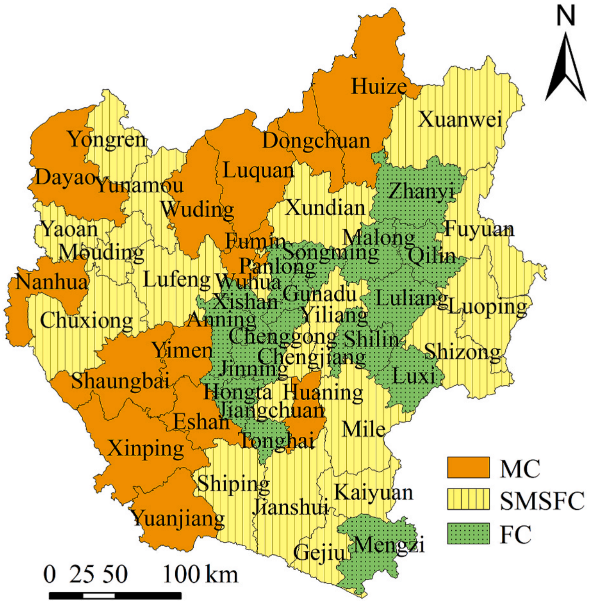

Fig. 4. Distribution map of FCs, SMSFCs, MCs in UACY.

3.2. Temporal and spatial variation of PLEF

3.2.1. Distribution characteristics

Fig. 5 shows the identification results of PLEF values in 2010 and 2020.

In 2010, 10 high-value and relatively high-value counties of PF in the central city of Kunming City, Hongta, Qilin, and Xuanwei, were all FCs and SMSFCs, which were flat and economically developed areas with a concentrated population and industrial clusters. 28 low-value and relatively low-value counties of PF, distributed in the west, were mainly MCs and SMSFCs, with insufficient conditions for large-scale agricultural production, dispersed population(Fig. 5a). As of 2020, the PF was generally enhanced, the high-value and relatively high-value counties increased to 12, were mainly FCs and SMSFCs, the low-value and relatively low-value counties decreased to 25, were mainly MCs and SMSFCs (Fig. 5d).

Counties with a high value and relatively high value of LF showed strong consistency with the PF. In 2010, 7 high-value and

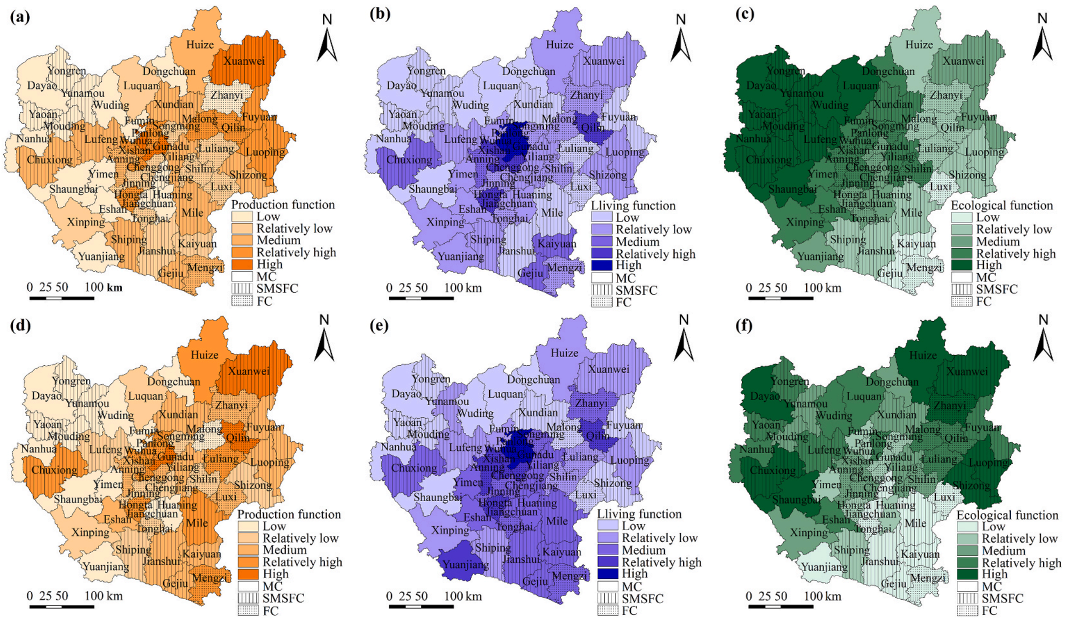

Fig. 5. Grade of the PLEFs in UACY for (a) 2010 PF, (b) 2010 LF, (c) 2010 EF, (d) 2020 PF, (e) 2020 LF, (f) 2020 EF.

relatively high-value counties of LF, were mainly concentrated in the main urban area of Kunming City, Qilin, Hongta, Chuxiong, Kaiyuan, and Gejiu, were all FCs or SMSFCs, the area had complete configuration of municipal infrastructure and public service facilities, developed transportation, a high degree of social security. 38 low-value and relatively low-value counties of LF, which were distributed around the edge, mainly in the northwest and southeast, were mostly MCs or SMSFCs with inefficient transportation, a scattered population, and insufficient facilities(Fig. 5b). As of 2020, the LF was generally enhanced, with the high- and relatively high-value counties increased to 9, were still FCs or SMSFCs. and the low-value and relatively low-value counties decreased to 24, were still MCs or SMSFCs. With the improvement of infrastructure and public service facilities, the LF in the southeast and central part were significantly improved (Fig. 5e).

In 2010, 25 counties are high-value and relatively high-value of EF, clustered in Chuxiong Prefecture and Huize, were MCs or SMSFCs, with a high proportion of woodland, grassland, wetland, and other ecological land and less ecological disturbance due to a sparse population. 14 counties are low-value and relatively low-value of EF gathered in the south and northeast, were FCs and SMSFCs (Fig. 5c). with an economic prosperity, population concentration, developed transportation, and a large number man-made disturbances led to a poor ecological environment-bearing maintenance function As of 2020, the high-value and relatively high-value counties of EF decreased to 20 mainly in the northwest, while Qujing City with the FCs and SMSFCs was pronouncedly improved. During the same time period, the low-value and relatively low-value counties increased to 19 significantly in the FCs and SMSFCs in the central, southern, and northwestern due to the strengthening of anthropogenic disturbance (Fig. 5f).

3.2.2. Balanced characteristics

Table 4 lists the G-value results of PLEF. From 2010 to 2020, G-value in different mountain-flatland types showed a general decreasing trend and the balance of function distribution was enhanced. G-value of the PF decreased from 0.3962 to 0.3326, which was close to the large difference to the barely uniform. The distribution differences stay relatively uniform in MCs, barely uniform to relatively uniform in FCs, and large differences to barely uniform in SMSFCs. G-value of LF decreased from 0.4399 to 0.3396, the distribution in MCs, SMSFCs, and FCs was relatively uniform, large difference, and barely uniform, MCs remained to relatively uniform, SMSFCs transformed to barely uniform, and FCs transformed to relatively uniform. G-value of EF decreased from 0.2268 to 0.1427, the distribution in MCS, SMSFCs, and FCs were uniform, relatively uniform, and uniform, the balance levels in MCS, SMSFCs, and FCs were all increased, the SMSFCs transformed to uniform.

The Theil index values were LF > PF > EF, respectively in Table 5.The T-value of PF in 2010 was 0.5213, decreased to 0.3838 in 2020. mainly produced by within the mountain–flatland feature group, with contribution rates of 65.72 % and 57.02 % in 2010 and 2020, was mainly caused by the imbalance from the FCs and the SMSFCs. The T-value of LF in 2010 was 0.9272, decreased to 0.6983 in 2020. The imbalance was produced mainly by within the mountain–flatland feature group, with contribution rates of 69.04 % and 69.75 % in 2010 and 2020, was mainly caused by the FCs and the SMSFCs. The T-value of EF in 2010 was 0.2389, decreased to 0.1379 in 2020, was overwhelmingly caused by the in-group unbalance, with contribution rates of 91.63 % and 75.40 % in 2010 and 2020, caused by SMSFCs, MCs, and FCs. the Gini coefficients and Theil index of the PLEF in the study area were both LF > PF > EF, and the equilibrium of the PLEF in UACY was EF, PF, and LF, in descending order.

3.2.3. Correlation characteristics

In 2010 and 2020, the global Moran's I indices of PF, LF, and EF exceeded 0 and passed the significance test, showing a significant positive spatial correlation, LF > EF > PF. The global Moran's I index of LF increased agglomeration, while the PF and EF decreased agglomeration and weakened in 2020 compared with 2010. Global autocorrelation exists for PF, LF, and EF, Fig. 6 shows the Local Moran's I results of PLEF.

From 2010 to 2020, the H–H counties of PF increased in Zhanyi and Fuyuan, mainly distributed in the central urban area of Kunming City, composed of FCs or SMSFCs, the L-L decreased in Wuding and Xinping in the northwestern MCs or SMSFCs, the H-L did not change in Hongta and Chuxiong, which were FCs or SMSFCs, the L-H decreased in Zhanyi and Chenggong, were mainly around the central of Kunming City which were FCs(Fig. 6a and d). The H–H of LF agglomerated in the central urban area of Kunming City, mainly composed of FCs, the L-L have not changed, mainly distributed in the northwestern Chuxiong Prefecture, which were SMSFCs and MCS. The H-L was Chuxiong with SMSFC, the L-H were mainly found in Kunming City, clustered around the H–H, composed of SMSFCs or FCs (Fig. 6b and e). The H–H counties of EF changed Significant distributed from northwestern SMSFCs and MCs in Chuxiong

Table 4
Gini coefficient of the PLEF.

Year	Mountain-Flatland types	Gini Coefficient (G)		
		PF	LF	EF
2010	UACY	0.3962	0.4399	0.2268
	MCs	0.2402	0.2219	0.1498
	SMSFCs	0.4087	0.4209	0.2875
	FCs	0.3228	0.3666	0.1622
2020	UACY	0.3326	0.3396	0.1427
	MCs	0.2805	0.2311	0.1136
	SMSFCs	0.3346	0.3133	0.1793
	FCs	0.2549	0.2934	0.1177

Table 5
Theil index of the PLEF.

Year	Function types	T	T_{BR}	T_{WR}	CT_{BR}	CT_{WR}	CT_1	CT_2	CT_3
2010	PF	0.5213	0.3426	0.1787	65.72 %	34.28 %	27.51 %	29.31 %	8.90 %
	LF	0.9372	0.6470	0.2902	69.04 %	30.96 %	36.14 %	23.53 %	9.37 %
	EF	0.2389	0.2189	0.0200	91.63 %	8.37 %	25.01 %	36.70 %	29.92 %
2020	PF	0.3838	0.2189	0.1650	57.02 %	42.98 %	24.15 %	23.79 %	9.08 %
	LF	0.6983	0.4870	0.2113	69.75 %	30.25 %	33.15 %	24.43 %	12.16 %
	EF	0.1379	0.1040	0.0339	75.40 %	24.60 %	22.76 %	30.63 %	22.01 %
Changes from 2010 to 2020	PF	−0.1375	−0.1237	−0.0137	−8.70 %	8.70 %	−3.36 %	−5.52 %	0.18 %
	LF	−0.2389	−0.16	−0.0789	0.71 %	−0.71 %	−2.99 %	0.90 %	2.79 %
	EF	−0.101	−0.1149	0.0139	−16.23 %	16.23 %	−2.25 %	−6.07 %	−7.91 %

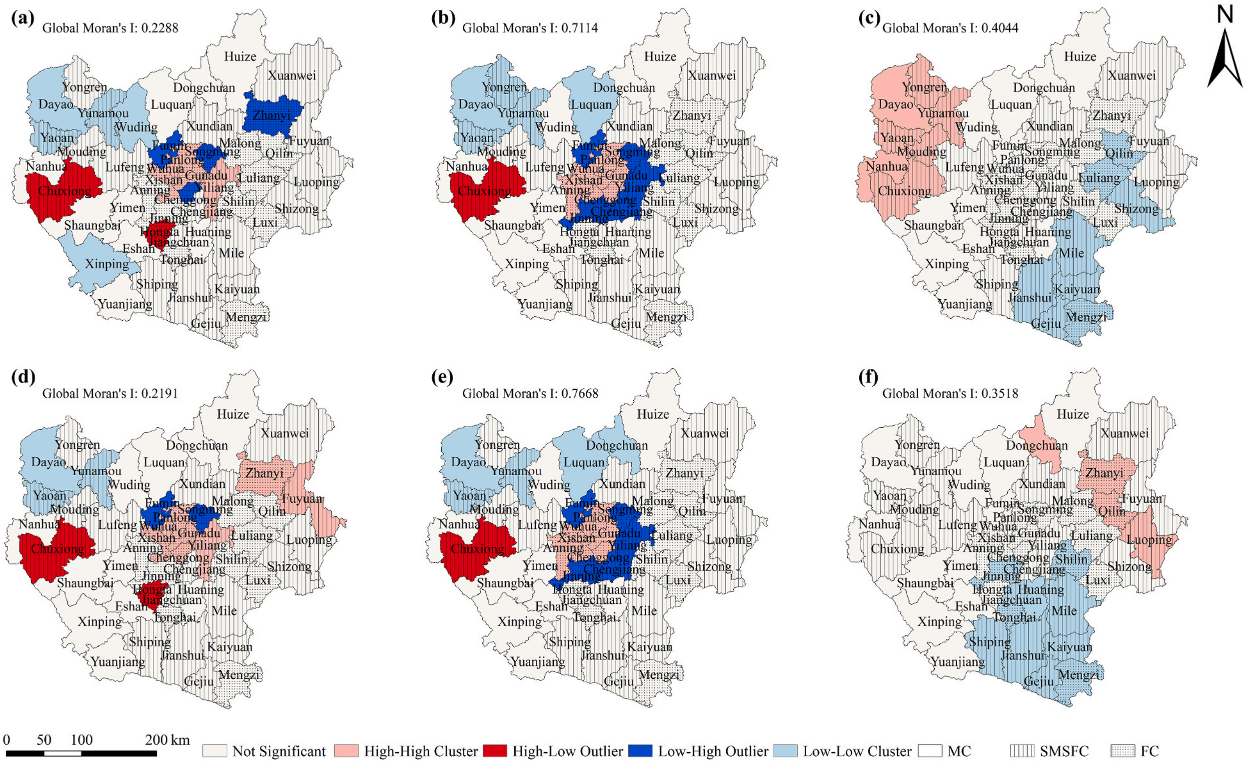

Fig. 6. Local spatial auto-correlations of the PLEFs for (a) 2010 PF, (b) 2010 LF, (c) 2010 EF, (d)2020 PF, (e) 2020 LF, (f) 2020 EF.

Prefecture to southeastern FCs mainly in Qujing City, no H-L and L-H was reported, the L-L also changed significantly from the southeast to the central and south, mainly composed of FCs or SMSFCs (Fig. 6c and f).

3.2.4. PLEF clustering characteristics

Fig. 7 presents the Gi* hot-spot results of PLEFs. From 2010 to 2020, the degree of concentration of high values of PF slightly decreased, and the low-value areas increased. In 2010, there are 11 hot-spot counties of PF in the central and northeastern, mainly in FCs and SMSFCs, and 2 cold-spot counties of in the northwest (Fig. 7a), in 2020, the hot-spot counties decreased to 9 in central of FCs or SMSFCs, the cold-spot counties increased to 5 in northwestern (Fig. 7d). There are 11 hotspot counties of LF concentrated in the central of FCs, no cold-spot county in 2010 (Fig. 7b), there was no change of hot-spot counties and appeared a cold spot county in the north in 2020 (Fig. 7e), There are 11 hotspot counties of EF in the northwestern, with SMSFCs or MCS, and 10 cold-spot counties in the southeast and east in 2010, with FCs or SMSFCs (Fig. 7c), the hot-spot counties decreased to 6 mainly clustered in the northwestern SMSFCs or FCS, and cold-spot counties increased to 13 in the central and southern in 2020, with FCs and SMSFCs(Fig. 7f). Hotspot areas of PF and LF were similarly distributed in the central part, and EF hotspot areas showed obvious reciprocity with PF and LF.

3.2.5. PLEF coupling coordination characteristics

Fig. 8 illustrates the CCD of PF-LF-EF, PF-LF, PF-EF, and LF-EF. From 2010 to 2020, the CCD of PF-LF-EF increased, and the two–two CCD increased. The CCD in the FCs, SMSFCs, and MCs also increased.

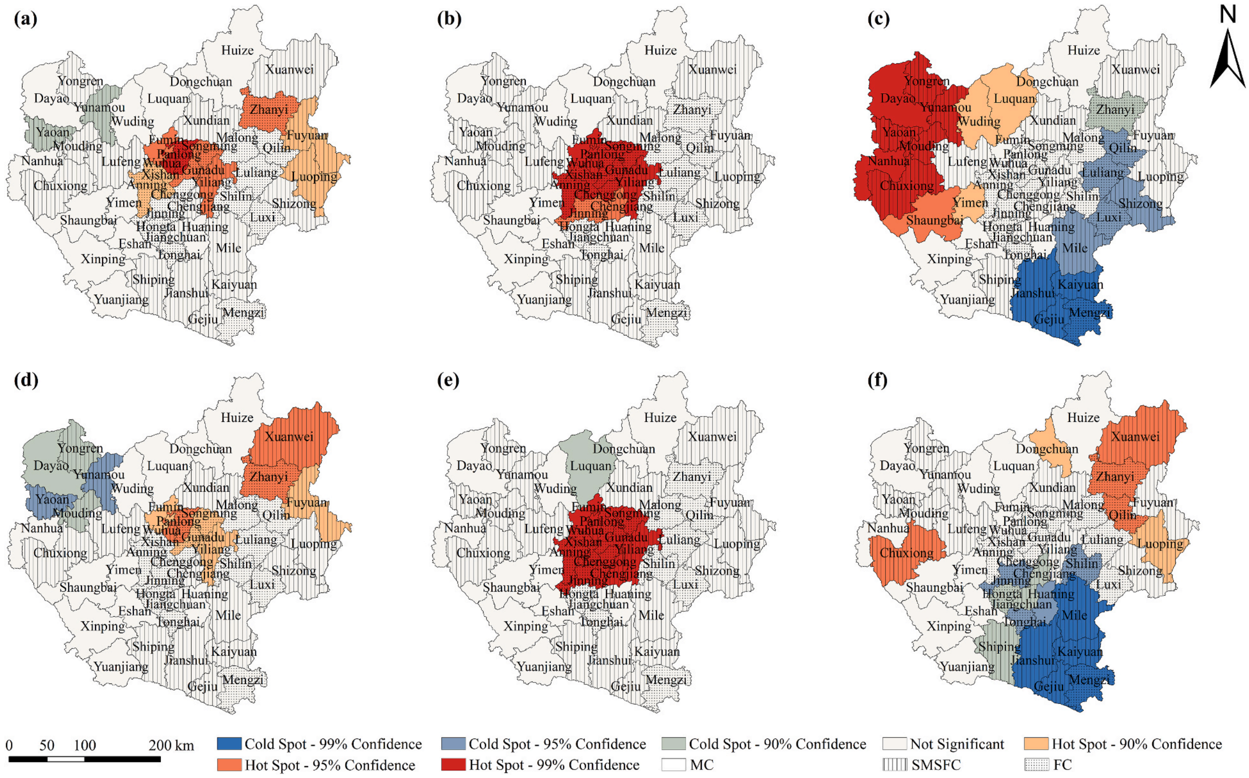

Fig. 7. Spatial distribution of the PLEFs in cold and hot spots for (a) 2010 PF, (b) 2010 LF, (c) 2010 EF, (d)2020 PF, (e) 2020 LF, (f) 2020 EF.

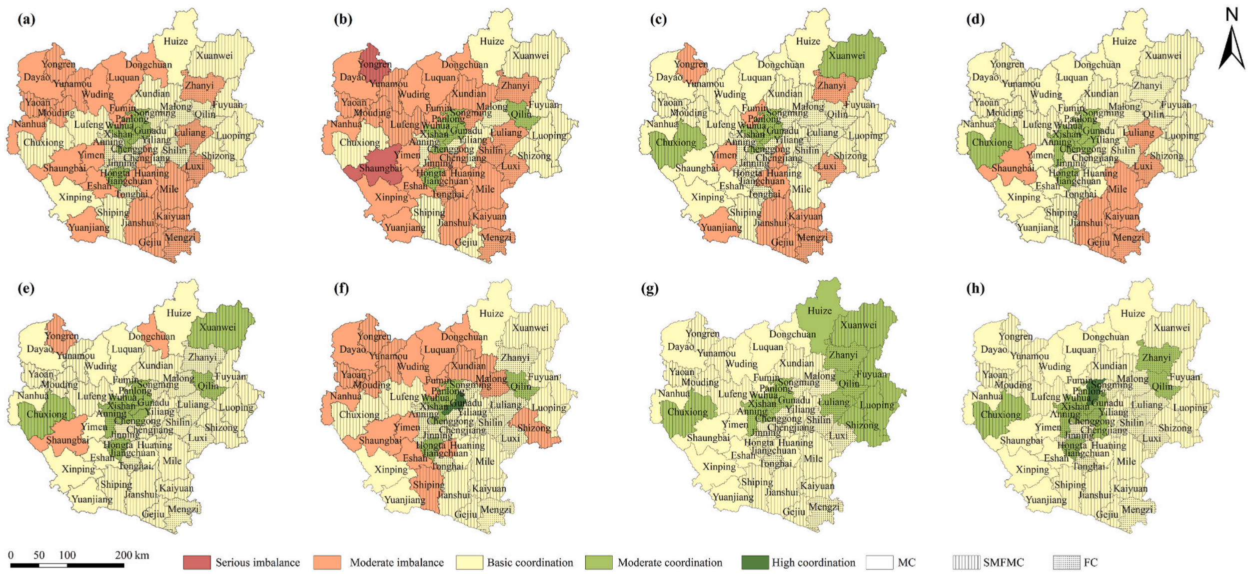

Fig. 8. Spatial distributions of coupling coordination degree of PLEFs for (a) 2010 PF–LF–EF, (b) 2010 LF, (c) 2010 PF–EF, (d)2010 LF–EF, (e) 2020 PF–LF–EF, (f) 2020 PF–LF, (g) 2020 PF–EF, (h) 2020 LF–EF.

In 2010, five moderately coordinated counties of PF-LF-EF were FCs mainly in the central, 19 basic coordinated counties were primarily SMSFCs and FCs in the central and northeast, and 25 moderately dissonant counties largely encompassed MCs or SMSFCs in the northwest and southeast (Fig. 8a). The level increased in 2020, Xuanwei, Qilin, and Chuxiong transferred to basic coordination, Anning and Chenggong transferred to moderate coordination, and considerable SMSFCs or MCs in the northwest and southeast changed from moderate dissonance to basic coordination (Fig. 8e).

In 2010, the CCD of PF-LF was high in the central region, while the western region exhibited a lower CCD. The dissonant counties were concentrated in the south and northwest, encompassing various mountain–flatland counties. The coordinated counties were primarily located in the central region, consisting of FCs, with two severely dissonant counties in the west were within SMSFCs and MCs (Fig. 8b). In 2020, considerable counties in the southwest transitioned from moderate imbalance to basic coordination, largely within FCs and SMSFCs(Fig. 8f). In 2010, the CCD of PF-EF was generally high in the central region and lower in the south. Dissonant counties were mainly located in the south, while coordinated counties were concentrated in the central with FCs (Fig. 8c). As of 2020, there was a significant increase in coordinated counties in the northeast, predominantly classified as FCS or SMSFCs, with all dissonant counties transitioning to basic coordination counties (Fig. 8g). In 2010, the CCD of LF-EF was high in the central region and low in the southeast. Specifically, dissonant counties were concentrated in the southeast, consisting of FCs and SMSFCs, while coordinated counties were largely located in the central region with FCs or SMSFCs (Fig. 8d). As of 2020, all the dissonant counties had transitioned to basic coordination counties (Fig. 8h).

3.3. *Comprehensive zoning and optimization*

The DF was determined in the PLEF in 2020 (Table 6). PF-dominant counties were dispersed across Xuanwei, Yiliang, Luxi, and Jianshui, mainly encompassing FCs and SMSFCs. LF-dominant counties were located in the central regions of Kunming City and Yuxi City, which also mainly encompassed FCs and SMSFCs. EF-dominant counties were located in western Chuxiong Prefecture and Yuxi City, primarily classified as MCs and SMSFCs. PLF-dominant counties formed clusters in the central and southeast regions, categorized as FCs and SMSFCs, PEF-dominant counties were clustered in the northeast, mainly consisting of SMSFCs or FCs. LEF-dominant counties were identified in the central region, classified as FCs or SMSFCs (Fig. 9).

We divide the study area into 18 functional areas (Fig. 10a) based on the principles of functional comprehensive zoning. Following the theory of sustainable development, the optimization of the comprehensive zoning of PLEF can fall into two approaches. One emphasizes the mutual coupling and coordination of PLEFs to establish a mutually beneficial relationship, the other prioritizes ecological development and the construction of a highland of ecological civilization construction. The optimized paths include the following:

(1) Combining adjacent functional areas of the same type into the same sub-district. (2) Highlighting ecological priority in mountainous counties. (3) MC and SMSC counties requiring functional coupling to form a functional coordination area, with the addition of only one coordination function in SMSCs. For instance, the PF functional superiority area can only be optimized as a PF-LF coordination area or a PF-EF coordination area. (4) Highlighting/weakening the function separately based on differential characteristics (significant hotspot areas/cold spot areas or HH/LL agglomeration counties). (5) Optimizing adjacent counties with similar functions for the same type. (6) Optimization based on a single hill-dam type; when multiple hill-dam types are involved, the number of hill-dam counties prevails. The specific optimization results yield 13 areas, as presented in Fig. 10b. The optimized areas include the following transformations: Mengzi transitions from PF-LF advantageous Area to PF-LF-EF coordination Area, Jinning shifts from LF-EF advantageous Area to PF-LF-EF coordination Area, Zhanyi, Luliang shifts from PF-EF coordination Area to PF-LF-EF coordination Area,

Table 6
NRCA index results of UACY.

County	NRCA			DF	Types	County	NRCA			DF	Types
	PF	LF	EF				PF	LF	EF		
Wuhua	0.0013	0.0073	−0.0087	PLF	MCMFC	Tonghai	−0.0007	0.0010	−0.0003	LF	FC
Panlong	0.0002	0.0067	−0.0069	PLF	FC	Huaning	−0.0007	0.0011	−0.0003	LF	MC
Guandu	0.0050	0.0063	−0.0113	PLF	FC	Yimen	−0.0020	0.0016	0.0005	LEF	MC
Xishan	0.0011	0.0040	−0.0051	PLF	FC	Eshan	−0.0020	0.0008	0.0012	LEF	MC
Dongchuan	−0.0016	−0.0016	0.0032	EF	MC	Xinping	−0.0000	−0.0007	0.0007	EF	MC
Chenggong	0.0002	0.0038	−0.0040	PLF	FC	Yuanjiang	−0.0008	−0.0005	0.0013	EF	MC
Jinning	−0.0015	0.0004	0.0010	LEF	FC	Chengjiang	−0.0019	0.0031	−0.0012	LF	MCMFC
Fumin	−0.0018	0.0002	0.0016	LEF	MC	Chuxiong	0.0009	−0.0014	0.0005	PEF	MCMFC
Yiliang	0.0009	−0.0008	−0.0002	PF	MCMFC	Shuangbai	−0.0026	−0.0029	0.0055	EF	MC
Shilin	−0.0005	−0.0005	0.0011	EF	FC	Mouding	−0.0019	−0.0014	0.0034	EF	MCMFC
Songming	−0.0007	0.0007	0.0001	LEF	FC	Nanhua	−0.0019	−0.0016	0.0034	EF	MC
Luquan	−0.0010	−0.0027	0.0037	EF	MC	Yaoan	−0.0021	−0.0018	0.0039	EF	MCMFC
Xundian	0.0005	−0.0024	0.0019	PEF	MCMFC	Dayao	−0.0022	−0.0025	0.0046	EF	MC
Anning	−0.0003	0.0023	−0.0020	LF	FC	Yongren	−0.0025	−0.0015	0.0040	EF	MCMFC
Qilin	0.0031	0.0011	−0.0042	PLF	FC	Yuanmou	−0.0015	−0.0011	0.0026	EF	MCMFC
Zhanyi	0.0004	−0.0015	0.0010	PEF	FC	Wuding	−0.0015	−0.0023	0.0038	EF	MC
Malong	−0.0016	−0.0019	0.0035	EF	FC	Lufeng	−0.0006	−0.0018	0.0023	EF	MCMFC
Luliang	0.0018	−0.0022	0.0004	PEF	FC	Gejiu	0.0010	0.0012	−0.0022	PLF	MCMFC
Shizong	−0.0004	−0.0026	0.0030	EF	MCMFC	Kaiyuan	0.0013	0.0011	−0.0024	PLF	MCMFC
Luoping	0.0009	−0.0022	0.0013	PEF	MCMFC	Mengzi	0.0025	0.0011	−0.0036	PLF	FC
Fuyuan	0.0010	−0.0032	0.0021	PEF	MCMFC	Mile	0.0032	0.0000	−0.0033	PLF	MCMFC
Huize	0.0016	−0.0035	0.0018	PEF	MC	Jianshui	0.0017	−0.0002	−0.0015	PF	MCMFC
Xuanwei	0.0044	−0.0043	−0.0001	PF	MCMFC	Shiping	0.0000	−0.0007	0.0006	PEF	MCMFC
Hongta	0.0006	0.0047	−0.0053	PLF	FC	Luxi	0.0019	−0.0004	−0.0015	PF	FC
Jiangchuan	−0.0012	0.0013	−0.0000	LF	MCMFC						

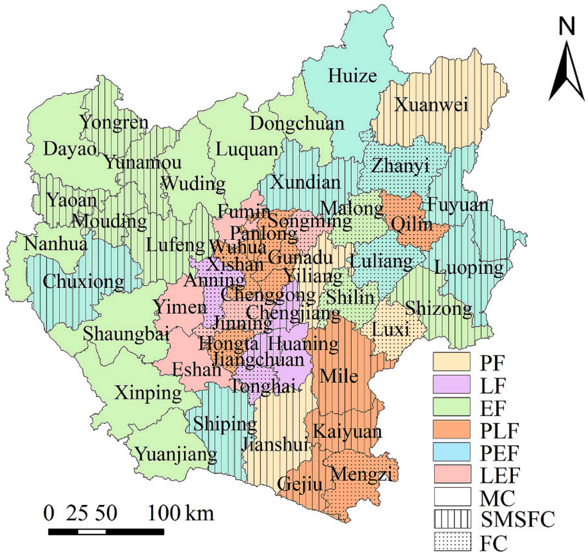

Fig. 9. Dominant functions of UACY in 2020.

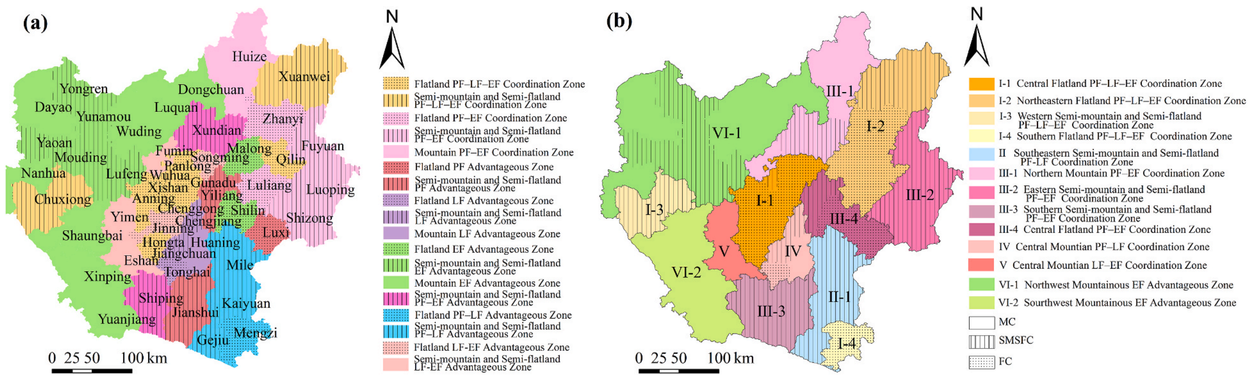

Fig. 10. Geographical space functional zoning (a), and optimization comprehensive zoning (b) of UACY.

Songming transitions from LF-EF advantageous Area to PF- LF-EF coordination Area, Malong move from EF advantageous Area to PF-LF-EF coordination Area, Jianshui transitions from PF advantageous Area to PF-EF coordination Area, Xundian shifts from PF-EF advantageous Area to PF-EF coordination Area. The paths of development are elucidated as follows:

I-1. Central Flatland PF–LF–EF Coordination Area encompasses the central urban area of Kunming and its expansion areas. This area aims to enhance its core leadership role and generate a positive impact on the neighboring regions. The objective is to establish a fast, convenient, and intelligent 1-h commuting circle, build the Kunming metropolitan area, optimize the industrial direction, and improve the added value of industries. Moreover, it is imperative to optimize the construction of infrastructure and public service facilities, carry out regional environmental management and ecological restoration, facilitate the sustainable and coordinated development of the PLEF, and build the engine of high-quality development of the urban agglomeration.

I-2. Northeast Flatland PF–LF–EF Coordination Area: the central city of Qujing and its expansion of Zanyi, Malong, Luliang and Xuanwei, it can guide the integrated development of town groups, build the Qujing town circle, consisting of Qilin-Zanyi-Malong-Luliang-Xuanwei, and actively integrate into the Kunming metropolitan area, using advanced manufacturing industry as a fulcrum, can drive economic development to form a high-quality livable city, integrate the development of regional medical, recreational, cultural, sports, and financial services, scientific research and innovation, and other functional centers, strengthen ecological protection and agricultural production in the flatland area, and maintain the coordinated development of the PLEF, built into a subcenter city.

I-3. Western Semi-mountain and Semi-flatland PF–LF–EF Coordination Area: Chuxiong in the west, taking the initiative to integrate into the urban agglomeration; promote industrial complementarity, strengthen the status of the geographical center of Yunnan; promote the common protection and governance of the ecological environment, infrastructure, and service facilities, including shared construction; and highlight the mountain and flatland area-differentiated town development guidance, should be built the city–town circle of Chuxiong as the rising growth pole in central Yunnan.

I-4. Southern Flatland PF–LF–EF Coordination Area: The southern region of Yunnan, specifically Mengzi, serves as a regional center and plays a crucial role in the core city of southern Yunnan. It is essential to enhance its position by promoting its integration into the Kunming metropolitan area, driving the development of surrounding counties, and establishing itself as a hub city for external development, particularly in coordination with neighboring Vietnam. Furthermore, concerted efforts should be made to ensure co-ordinated protection and governance of the Red River Basin with surrounding counties and Vietnam, utilizing multiple natural parks to improve and restore the ecological environment. The consolidation of the manufacturing industry, new materials, modern logistics, cultural and tourism industries, as well as plateau characteristic agriculture, is vital to achieving sustainable and environmentally friendly development.

II. Southern Semi-mountainous and Semi-flatland LF-EF Coordination Area: This area encompasses Honghe Prefecture, Gejiu, Kaiyuan, and Mile, which are undergoing urbanization development. The optimization focus should be on cultivating the Honghe town circle, comprising Mengzi-Gejiu-Kaiyuan-Mile, to leverage the agglomeration effect and enhance the city level and regional core driving role. Simultaneously, emphasis should be placed on improving the quality of the ecological environment by restoring the Pearl River and Yuan River ecosystems comprehensively.

III-1. Northern Mountain PF–EF Coordination Area: This area, including Huize, Xundian, and Fumin, is a significant agricultural production, industrial production, and ecological conservation region surrounding the central city of Kunming and Qujing town circle. The optimization efforts should focus on leveraging the location and unique conditions to enhance plateau featured agriculture and plantation, ensure a stable supply of agricultural products to the main urban area, activate and utilize the vast natural reserves and historical cultural resources. Additionally, the area should be developed for ecological tourism and tourism agriculture to address infrastructure limitations, improve living standards, and strengthen biodiversity protection and soil erosion control.

III-2. Eastern Semi-mountainous and Semi-flatland PF-EF Coordination Area: This area comprises Luoping, Shizong, and Fuyuan, peripheral counties of Qujing city. The primary emphasis should be on agricultural production, accommodating the industries and population of the main urban area. With superior agricultural production conditions, this area should play a critical role in the ecological functions of the region, considering the higher risks of stone desertification and soil erosion. Optimization efforts should focus on vegetation restoration and zoning, promoting ecological restoration, conserving water-conserving forests and ecosystems in the Pearl River source area, establishing a robust ecological security barrier at the source of the Pearl River, integrating into the Qujing town circle for new urbanization and urban-rural integration development, and creating special agricultural planting and green food production areas to safeguard food production and supply capacity.

III-3. Southern Semi-mountain and Semi-flatland PF–EF Coordination Area: This area, encompassing Shiping and Jianshui of Honghe Prefecture, is rich in historical and cultural heritage. The optimization efforts should concentrate on strengthening agricultural production, promoting intensive processing of agricultural products, protecting ancient cities and towns systematically, activating historical-cultural areas, and safeguarding Yilong Lake. Additionally, the area should focus on building characteristic towns and beautiful villages, optimizing the "one lake, two cities" protection and development pattern, managing ecological restoration of soil and water conservation in the Red River Valley, addressing infrastructure deficiencies, and improving living standards.

III-4. Central Flatland PF–EF Coordination Area: This region, situated between Kunming, Qujing, and Honghe central urban areas, includes Yiliang, Shilin, and Luxi. The ecological environment in this area is fragile due to extensive rocky desertification. Simultaneously, it possesses advantageous characteristics for tourism. Optimization efforts should focus on improving the level of industrial development and agglomeration, integrating it further into the Kunming metropolitan area, fostering new patterns of green development with vitality. Additionally, the area should prioritize the development of tourism and service industries, special agriculture, and establish itself as an internationally renowned tourist destination and modern special agricultural base.

IV. Central Mountain PF–LF Coordination Area: This area includes Fuxian Lake, Xingyun Lake, and Qilu Lake, characterized by highland lakes. It offers favorable conditions for agricultural production and tourism industries, particularly in the core water-protection area. The optimization focus should be on ecological protection of the water systems, implementing lake management, and strengthening water-quality management in Qilu Lake, Xingyun Lake, and Fuxian Lake. Moreover, efforts should be made to restore the watershed's ecological balance, improve ecological functions, revitalize natural and historical-cultural resources, develop ecological tourism centered around the lakes, and promote coordinated development of ecological, agricultural, and tertiary industries.

V. Central Mountain LF–EF Coordination Area: the expansion area of industries in the main urban area of Kunming, including Yimen and Eshan. The focus of optimization is to undertake the industries in the main urban area of Kunming, optimize the industrial structure, strengthen the scientific and technological leadership, focus on guiding the green modern industrial agglomeration, build green steel city and a green mining and metallurgy cluster, accelerate the development of plateau featured agriculture and tourism culture, and develop agricultural industries such as vegetable, leisure, sightseeing, and green food processing. Coordinate ecological protection and increase ecological protection and restoration in ecologically fragile areas.

VI-1. Northwest Mountainous EF Advantageous Area: the end of the Yunling Mountains and the upper reaches of the Jinsha River area, mainly including counties in Chuxiong Prefecture It is an important barrier to undertake regional ecological security. The focus should be to give full play to its ecological advantages; prioritize ecological security; carry out soil and water conservation, afforestation, and ecological restoration projects; promote the construction of the nature reserve system; enhance the water EFs of the Jinsha River; build an ecological barrier for urban clusters; give full play to its EF-related advantages; create ecologically attractive spaces; and realize revitalized utilization.

VI-2. Southwest Mountainous EF Advantageous Area: the southwest of the Ailao Mountain and Red River ecological protection core area, including Shuangbai, Xinping, and Yuanjaing.This is an important barrier to the province's ecological security. The focus should be to concentrate on biodiversity protection; prioritize ecological security; carry out ecological restoration projects and soil erosion control; promote the construction of the Ailao Mountains National Park, the reasonable development and use of natural landscape tourism resources, the organic integration of mountain- and water-integrated protection; and to build a solid ecological security barrier in the province.

4. Discussion

The investigation of productive-living-ecological space constitutes a significant aspect of territory spatial planning. Territorial space is a system comprised of geographic conditions, natural resource endowment, economic development, population concentration and other contributing factors. The PLE spaces, which delineate spatial divisions based on production, living conditions, and ecological considerations, serve as fundamental elements within territorial space. The distribution and evolution of these elements play a crucial role in determining the potential for sustainable development within a given study area. Consequently, the study of PLEF has garnered substantial attention within China's territorial space planning [54]. Exploring and analyzing the interrelationships, roles, and evolutionary patterns among PLEF can aid in formulating policies that promote sustainable development within diverse regional contexts.

4.1. PLEF identification index system

The evaluation outcomes of the PLEF serve as a basis for equilibrium analysis, agglomeration patterns, coupling coordination, and so forth. The evaluation index system has been extensively adopted to identify PLEF [16,41]. Constructing a hierarchical and categorical index system facilitates comprehensive and standardized index selection. In this paper, we comprehensively consider the accessibility of data, deconstructed the objectives in order of target layer, criterion layer, and index layer, and we build an index system to identify the PLEF. Notably, the economic and social data originate from authoritative statistics such as Yunnan Statistical Yearbook, while the land use data are sourced from the province's change survey database. These sources offer higher precision and accuracy compared to land use cover data. Among the outcomes of the identification of the PLEFs, the high-value areas of PF and LF exhibited strong consistency, similar to the conclusions reached in the previous studies [55]. These areas are mainly economically developed areas in the flatland, aligning with the understanding that PF and LF depend on production materials. In addition, the population is clustered in the flatland area. The high-value areas of EF are mainly distributed in MCS, which are somewhat complementary to the LF and PF. This is basically consistent with the conclusion [56]. Furthermore, the analysis of clustering characteristics reveals that PF and LF demonstrate a strong dependence on flatland areas, while EF exhibits a notable reliance on mountainous water systems. This observation is largely in agreement with previous research results [57].

4.2. Comprehensive evaluation index of mountain-flatland

Within the expansive land of China, there exists a diverse terrain, with mountainous regions accounting for two-thirds of the national land area. This landscape presents notable contradictions in land use. Conducting a study on the PF, LF and EF within mountain dam areas helps us to understand comprehensively the characteristics and problems of function distribution under different types of mountain dams, to yield suitable solutions to realize the coordinated development of economy, society and environment, and to guide the allocation of spatial resources in different ways. It is of great value in formulating sustainable development strategies, promoting regional development and improving the quality of life of residents. This is the key point and challenge for optimizing the territorial space in mountain and flatland areas [58]. To facilitate the study of productive-living-ecological (PLE) space, a methodology is needed to categorize mountain-flatland types as a geographic foundation. The evaluation model constructed in this paper demonstrated a high degree of consistency with the original study [41], with an 83.67 % match. However, the original study classified Panlong, Xishan, Hongta, and Mengzi as semi-mountain and semi-flatland counties (SMSFCs), whereas this paper classified them as flatland counties (FCs). In reality, these four counties represent the core area of the city (prefecture), aligning more closely with the characteristics of population, economy, and industry "gathering according to the flatland." Consequently, our evaluation results better reflected the natural, economic, and social clustering characteristics.

4.3. Gini coefficient and Theil Index

Changes in things can be categorized into overall changes and local changes within a system. This paper primarily focuses on the characteristics of the overall distribution of the PLEF, and then explore the clustering pattern and change characteristics in 2010 and 2020. The Gini coefficient and the Tel index are indices adopted for measuring the degree of socio-economic inequality, and existing studies have shown that the two methods are effective in exploring the differences in the overall economic distribution of the region [59], and that the two methods can be calibrated against each other, it can provide an objective way of measurement, and an important guide for policy evaluation [60], previous research had explored the equilibrium based on resource and non-resource cities [61], but no scholars have conducted a study on the balance of PLEF based on the characteristics of mountain–flatland. The Gini coefficient and the Theil index introduced in this paper contribute to the analysis of the degree of imbalance as LF > PF > EF, all of which are mutually verified and complementary, proving the feasibility of the research method. The intra-group and inter-group contribution rates of the Theil index were employed for the in-depth analysis of the association between the causes of the unbalanced distribution of functions and the characteristics of mountain–flatland. The intra-group contribution of PLEF spatial Theil indices was greater than the inter-group contribution, which provided a basis for the subsequent analysis of the spatiotemporal divergence of PLEF. The function in so the article continues to analyze the clustering and evolution law of the three functions inside the study area through correlation analysis and hotspot analysis, respectively, the two methods have been exploited by scholars for the analysis of the problem [62,63], this paper draws on the two methods to analyze the law of change within the function from inside the study area, and the results of the study indicates that topography and geomorphology are important reasons for the influence of the PLEF, further verifying that PF and LF have strong flatland dependence, while the EF have strong mountain dependence.

4.4. Coupling coordination degree

The CCD theory aims to address the interrelationships and coordination between the components of a system. Existing studies have demonstrated that the coupling theory plays an effective role in testing the association between multiple systems that interact with each other. The CCD of PF, LF and EF refers to the effective coordination and integration of these three aspects in the context of sustainable development to realize the common goals of economic development, people's life improvement and environmental protection. This paper describes the spatial and temporal characteristics of the evolution of the CCD between PF, LF, and EF, as well as between the two in the study area from 2010 to 2020 by utilizing the CCD index. The production-living-ecological-dissonant area was entirely contained within the production-living-dissonant area, except for Gejiu. The production-living-ecological dissonance was primarily caused by production-living dissonance. Wuhua, Panlong, Guandu, Xishan, and Hongta are areas that exhibited coordination with each other, forming the production-living-ecological-dysfunctional area. As urbanization and economic development progress, accompanied by improvements in living conditions and increased investment in ecological protection, PF, LF, and EF become more coordinated, resulting in the formation of the PLEF coordination area. Additionally, this paper demonstrates the effectiveness of CCD in measuring the consistency and interaction between subsystems (PF, LF, and EF) within a region.

4.5. Functional comprehensive zoning

The ideal state of PLEFs is to achieve a balance of PF, LF and EF, the synergistic association between PLEFs with mutual gain and orderly development is the basis of sustainable regional development. If the functions are in a state of disorder and chaos, hindering the sustainable development of the region, the benign coupling between the three functions tends to develop toward orderly development, manifested as a benign state for the development and protection of national space. Thus, based on the comparative advantages among the PLEFs, the functional advantage area was determined. The EF advantageous areas should highlight EFs and the remainder of the advantage areas should enhance the coupling coordination type to promote the orderly development of the PLEF, combined with the 10 areas optimized by the characteristics of the mountain flatland. PF-LF-EF coupling coordination area includes Kunming City, Qujing City, Yuxi City Chuxiong Prefecture, and other central cities, secondary-central cities, and sub-central cities, PF-EF coordination area is generally based on agro-industry and ecological protection, LF-EF coordination area is the regional central city or the backup area for urban expansion, and the EF advantage area is the city cluster and the important ecological barrier of the province. Optimized zoning is generally in line with the relevant regional positioning and planning development objectives of the *Yunnan Provincial Territorial Spatial Planning* and *Urban Agglomeration in Central Yunnan Planning*. The spatial zoning model proposed in this paper, emphasizes the level of coupling coordination of spatial PLEFs [64], and considers the advantageous function, especially the EF [65]. The zoning results are more in line with reality. This can provide some theoretical reference for the functional zoning in the spatial planning of the land.

4.6. Limitations and future research

Compared with the previous studies, we have improved the PLEF identification index system, comprehensive evaluation index of Mountain-Flatland, etc. Meanwhile, a new zoning method and optimization path are proposed. However, it is important to acknowledge that the modeling process in this study has certain limitations due to the restricted availability of data and incomplete knowledge. Consequently, there is scope for further advancements in the proposed models. Firstly, the comprehensive evaluation index developed for the flatland area in this research can be strengthened by conducting validation studies in different study areas. Considering the constraints related to data collection, it is recommended to optimize the function evaluation index system for specific characteristic areas by incorporating the actual circumstances. Secondly, the identification of the PLEF components in this study does not account for the differentiation of functions within the administrative district. To mitigate subjective biases, it is advisable to select evaluation indices for subsystems based on theoretical analyses. For instance, in the evaluation of EFs, additional indices such as the biodiversity index and the level of compliance with water quality standards can be included. Thirdly, it is proposed to refine the differentiation of PLEF within the administrative districts. This involves investigating the mechanisms underlying the development of PLEF in different counties from both macroscopic and microscopic perspectives, considering various scales. Furthermore, it is crucial to explore the factors that influence the imbalance of the three functions and examine the spatial and temporal variations. This research should encompass an in-depth analysis of the factors driving the uneven distribution of the three functions, taking into account both macro and micro aspects. Future research directions should focus on the refined study of the differentiation of the PLEF within the administrative units. Moreover, it is necessary to explore the mechanism of the development of the PLEF in different counties from macro and micro perspectives according to different scales.

5. Conclusion

In this study, the UACY (name of the study area) was selected as the geographic region of investigation. The primary objective of this research was to develop a comprehensive evaluation framework for assessing the mountain-flatland area. A function identification evaluation system was constructed utilizing data from 2010 to 2020. To analyze the degree of imbalance in the PLEF space, the Theil index and Gini coefficient were employed. Spatial modeling techniques were employed to examine the temporal and spatial changes in PLEF, while the CCD model was utilized to quantitatively measure the level of coordination between the PLEF components. The NRCA method was used to determine the dominant functions, establish functional zones within the national territory, and propose an optimization scheme based on the principles of sustainable development. Differentiated development and control paths were recommended to achieve sustainable development. The key findings of this study are as follows.

(1) The study area exhibited a general pattern characterized by western MCs/SMSFCs, central FCs, and eastern SMSFCs. The PLEFs demonstrated distinct clustering and mountain-flatland characteristics. PF was predominantly concentrated in the central and northeastern FCs and SMSFCs, while LF exhibited high concentration in the central FCs. EF was distributed in the MCs and SMSFCs in the northwest. High-value areas of LF and PF exhibited strong consistency and were complementary to EF.
(2) The degree of imbalance in PLEF was observed in the following order: LF > PF > EF, with SMSFCs > FCs > MCs. This imbalance increased from 2010 to 2020, primarily driven by intra-group factors within the mountain-flatland areas. The spatial agglomeration degree followed the pattern LF > EF > PF, with LF and EF showing an increasing trend while PF decreased. PF exhibited clustering in the central FCs or SMSFCs, LF demonstrated strong clustering in the central FCs, and EF displayed general clustering in the MCs or SMSFCs. High-value agglomeration decreased, while low-value areas increased significantly.
(3) PF-dominant, LF-dominant, EF-dominant, LEF-dominant, and PLF-dominant areas exhibited typical mountain-flatland characteristics. The coupling coordination types among the PLEFs were primarily categorized as basic coordination, moderate dissonance, and moderate coordination with varying mountain-flatland characteristics. From 2010 to 2020, the inter-functional coupling coordination degrees among FCs, SMSFCs, and MCs showed an overall upward trend, with several counties transitioning from moderate dissonance to basic coordination.
(4) The UACY was divided into 18 functional areas across 8 categories, which were further optimized into 13 comprehensive areas based on divergent characteristics and functional orientations. Targeted optimization suggestions were proposed by considering regional characteristics, aiming to provide guidance for the protection and development of the territorial space in mountain and flatland areas.

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Ethics Declarations

All participants provided informed consent to participate in the study.

Data availability statement

Has data associated with your study been deposited into a publicly available repository?
No.
Please select why.
Data will be made available on request.

CRediT authorship contribution statement

Yongping Li: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Shuqing Zhang:** Funding acquisition, Conceptualization. **Junsan Zhao:** Writing – original draft, Methodology, Funding acquisition. **Guangri Zhang:** Supervision. **Guoxun Qu:** Resources, Investigation, Formal analysis. **Shilin Ma:** Writing – review & editing, Resources. **Xiaobo Liu:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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