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Coupling and Coordination Relationship of Economic–Social–Natural Composite Ecosystem in Central Yunnan Urban Agglomeration

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Abstract: Exploring the spatio-temporal differentiation characteristics and coupling coordination relationship of the composite ecosystem of urban agglomerations is of great significance for promoting the synergistic sustainable development and integration construction of urban agglomerations. This paper is based on LUCC (Land Use and Land Cover Change) data, a DEM (Digital Elevation Model), and temperature, precipitation, and other multi-source data, using the central Yunnan urban agglomeration as an example and constructing a multi-dimensional evaluation index system highlighting development quality and efficiency. The entropy weight method was first used to determine the comprehensive weights to evaluate the regional economic and social development level. Then, the InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) model was used to quantitatively calculate and analyze the spatial and temporal evolution characteristics of the four key ecosystem services, evaluating the spatio-temporal evolution characteristics of the natural subsystem. The coupling coordination model was used to quantitatively analyze the evolution of the coupling coordination of the composite ecosystems in the central Yunnan urban agglomeration during the period of 2010–2020, and to reveal its development law. The results show the following: ① During the study period, the socio-economic subsystems in the central Yunnan urban agglomeration demonstrated an outward radiative growth from Kunming City, marked by underdeveloped sub-centers and prevalent low-level areas. ② Trends in ecosystem services varied, with water and soil conservation showing fluctuating increases, carbon sequestration remaining stable, and habitat quality declining. The critically important integrated ecosystem services zone of the natural subsystem is mainly located in the northeastern region and southwestern edge of the study area. ③ In 2020, the coupling coordination degree of the composite ecosystem was 0.9492. This showed that economic, social, and ecological subsystems are highly coupled, with consistent overall development trends and strong interactions. ④ The increase in the degree of harmonization amounted to 7.82%, with lagging subsystems varying in the degree of harmonization in subregions. This study can provide a scientific foundation for the development of policies for the Central Yunnan urban agglomeration, promoting regional sustainable development and optimizing the spatial pattern of the national territory.

Keywords: composite ecosystem; coupling coordination degree model; spatio-temporal differentiation characteristics; central Yunnan urban agglomeration

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1. Introduction

Social, economic, and natural elements together constitute a composite ecosystem on which human beings depend for their survival and development [1]. The three subsystems are interconnected through the flow of energy, matter, and information to form a higher level coupled system [2]. The report of the 20th National Congress of the Communist

Party of China explicitly stated that one of the essences of Chinese-style modernization is the harmonious coexistence between humans and nature. Sustainable development is essentially about the harmonious progression of relationships among the human living environment, the material production environment, and the socio-cultural environment. There exists a dialectical unity between ecological protection and economic–social development. The development of regional economies is inevitably dependent on a sound ecological environment as its foundation. The coordinated development between ecology and economy represents a green, sustainable mode of development. Composite ecosystem theory provides an important foundation for the study of complex human–land systems. Only by realizing their coordinated development and forming a virtuous circle can we ensure the long-term stable development of the social system, which is of great guiding significance to the realization of sustainable development [3].

Currently, the theory of composite ecosystems has been widely applied to many fields such as human habitat [4], natural sciences [5], and social management [6]. As ecosystem services are closely related to human well-being, the coupled relationship between urban economic development and the ecological environment has become a central issue in regional development research. The coupling-coordination model is a classic method in the study of human–land relationships, capable of considering multiple dimensions such as economy, ecology, and society to more comprehensively reflect the quality and level of regional development. Moreover, the coupling-coordination model can reveal the characteristics and interrelationships between economic development and ecological environmental changes from a spatiotemporal perspective, providing a scientific basis for formulating policies and management strategies. Research on the coupling and coordination of multiple elements and systems has become an important part of regional development research. Thematically, more research is focused on the coupling and coordination between the ecological environment and the two systems of economy [7–9] and society. Methodologically, scholars have mostly used the entropy weight method [10], coupling coordination degree model [11,12], and other methods to measure the degree of coupling coordination between systems. Geographically, the scope of inquiry encompasses large scales, such as the whole country [13] and the central region [14], the provincial (municipal) level in Fujian [15], Jiangsu [12], and Jilin [16], and urban agglomerations, such as Beijing-Tianjin-Hebei, the Yangtze River Delta [17], the Pearl River Delta [18], and the Central Plains [19,20]. However, current research is still lacking. Firstly, previous research has primarily focused on the coupling and coordination studies between economic and natural subsystems, with insufficient consideration of the social subsystem and a lack of comprehensive social development level evaluation indicators. Secondly, there is inadequate attention to the coupling and coordinated development of regional composite ecosystems in plateau and mountainous areas, which are characterized by unique geographical locations, significant spatial differences in resource allocation, and imbalanced socio-economic development. Thirdly, traditional studies on regional ecosystem states often rely on single statistical approaches. The natural characteristics of the ecosystem may therefore be neglected, making the assessment results not a true reflection of the actual ecological state of the region.

The central Yunnan-China urban agglomeration is one of the 19 major urban agglomerations supported by the national strategy [21]. It is located in the convergence zone of several important national strategies, such as "One Belt, One Road", the "Yangtze River Economic Belt", and the "New Land and Sea Corridor in the West", and serves as a crucial gateway to South Asia and Southeast Asia. However, despite the region's rapid economic development, the region faces marked disparities in urbanization levels among its cities and towns, coupled with suboptimal infrastructure connectivity. Concurrently, rapid economic development has brought about changes in land-use patterns and pressure on the ecological environment, with problems such as the over-exploitation and irrational use of natural resources, declining biodiversity, and the fragmentation of ecosystems. Such imbalances between economic and social advancement and the ecological environment pose a threat to the region's sustainable development. This paper starts from the premise of the mutual influence among the economic, social, and natural systems, adopting a research perspective focused on high-quality sustainable development. By de-emphasizing aggregate indicators, it constructs an evaluation index system that highlights development quality and efficiency, thereby enhancing the comprehensiveness, extensiveness, and holism of the urban agglomeration's composite ecosystem study. Furthermore, the coupling coordination degree model was utilized to study the interactive coupling relationship of the composite ecosystem. This paper aims to unveil the spatiotemporal distribution patterns and synergistic evolution mechanisms of the composite ecosystem of the Central Yunnan urban agglomeration. It is intended to offer a scientific reference and basis for advancing the ecological civilization construction and high-quality sustainable development of the region.

2. Materials and Methods

2.1. Overview of the Study Area

The central Yunnan urban agglomeration, a pivotal urban cluster in central Yunnan Province, is positioned south of Dianchi Lake, with geographical coordinates from 24°26′ N to 37°38′ N and from 98°55′ E to 105°55′ E (Figure 1). It includes all of Kunming City, Chuxiong Prefecture, Yuxi City, Qujing City, and the northern part of Honghe Prefecture in Yunnan Province, covering 49 counties and districts, with a total area of about 25,000 square kilometers.

The city cluster stands out as the most intensively developed region in Yunnan Province, boasting robust economic connections, an advanced transportation network, a solid development foundation, and significant potential for future growth. Kunming City, as the centerpiece, is at the forefront of developing modern service sectors, high-tech industries, and tourism. Surrounding cities like Qujing City and Yuxi are also critical to the province's economic surge, contributing significantly through mineral resources, agriculture, and tourism sectors.

The region's high-altitude, mountainous landscape endows it with abundant natural resources and a rich biodiversity, further enhancing its economic and ecological value. It is not only a key urban cluster in Southwest China but also serves as a vital corridor linking the region with Southeast Asia. Its strategic location and dynamic development play an instrumental role in fostering regional and national progress.

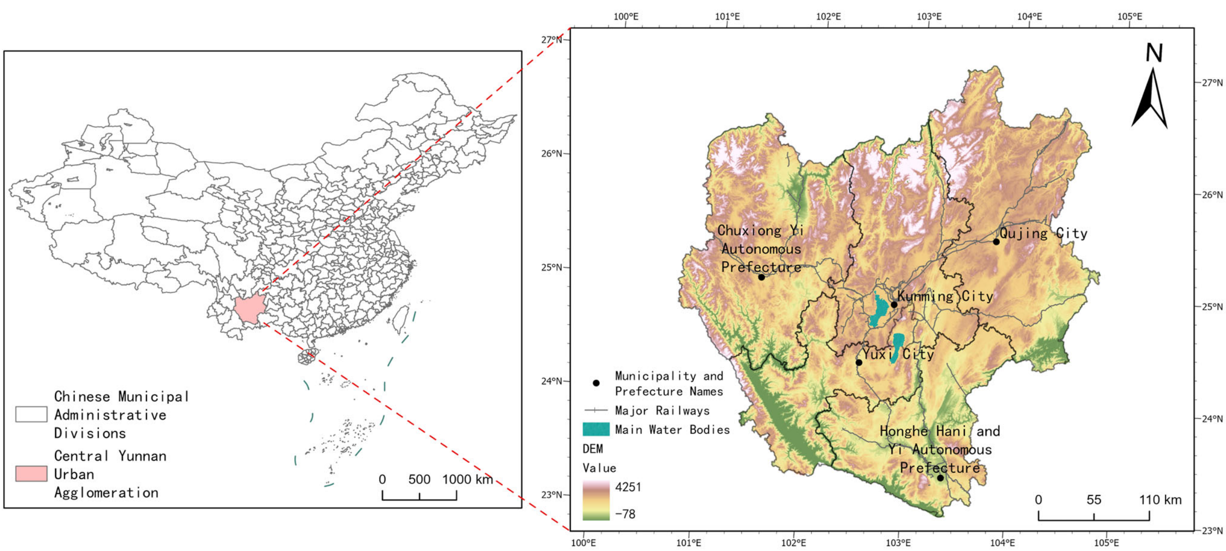

Figure 1. Study area scope.

2.2. Data Sources

The main data sources in this paper include economic and social data, basic geographic data, and meteorological data. Economic and social data cover information on industry, population, income, and urban construction. These data are mainly from the

China Statistical Yearbook, Yunnan Statistical Yearbook, and Yunnan City Yearbook, as well as the statistical yearbooks and statistical bulletins of cities and states. The basic geographic data cover critical elements such as the road networks, river systems, and administrative boundaries of districts and counties, and are procured from the National Center for Basic Information, ensuring accuracy and relevance. Meteorological data, including indicators of temperature, precipitation, and water pressure, were obtained from the National Weather Science Data Center. Specific data sources are detailed in the Table 1.

Table 1. Key data and their access routes, pre-processing.

Data	Source	Preprocessing
Meteorological data such as temperature, precipitation, actual water pressure, etc.	Weather Science Data Center (http://data.cma.cn (accessed on 7 July 2023))	To account for inter-annual fluctuations in the data, local annual average meteorological data were selected for the calculations.
Potential evapotranspiration		Annual mean potential evapotranspiration was calculated using the Modified-Hargreaves method with refined interpolation.
DEM data	Geospatial Data Cloud (https://www.gscloud.cn (accessed on 8 July 2023))	The ASTER GDEM 30 m resolution data of the urban agglomeration in central Yunnan were obtained and cropped and spliced by ArcGIS. The watershed boundary was obtained by ArcGIS hydrological analysis.
Soil depth data, soil type data, and other soil data such as organic carbon content	Earth System Science Data Sharing Platform, Cold and Arid Regions Science Data Center, China Soil Dataset Based on World Soil Database	PAWC and saturated hydraulic conductivity were calculated using soil properties from the SPAW Hydrology model.
Land use data	Center for Resource and Environmental Sciences and Data, Chinese Academy of Sciences (http://www.resdc.cn (accessed on 3 July 2023))	The time span included 2000, 2015, and 2020, and the resolution was 100 m × 100 m. After data processing and with reference to the national county-level land use status classification system, a land use classification map of the urban agglomeration in central Yunnan was generated.

2.3. Construction of Indicator System and Determination of Weights

The composite ecosystem is a unified ecological function system composed of human society, economic activities, and natural conditions, and consisting of three subsystems: economic, social, and natural, each containing multiple evaluation indicators. Due to the different measurement units of these indicators, a direct comparison between them is not feasible. Moreover, each indicator has both positive and negative effects on the subsystems. A positive effect means that a higher value of the indicator corresponds to better performance of the subsystem; conversely, a negative effect indicates that a higher value results in worse performance of the subsystem. Therefore, to eliminate the issues caused by measurement units and the positive and negative effects, this study needs to standardize the indicators within the subsystems. The formula for standardization is as follows:

$$x'_{itj} = \begin{cases} \frac{x_{itj} - \min(x_{itj})}{\max(x_{itj}) - \min(x_{itj})}. & \text{positive indicators} \\ \frac{\max(x_{itj}) - x_{itj}}{\max(x_{itj}) - \min(x_{itj})}, & \text{negative indicators} \end{cases} \tag{1}$$

In the formula, x_{itj} represents the sample value of indicator j for region i in period t; max and min, respectively, denote the maximum and minimum values of indicator j in region i; and the standardized value of x'_{itj} ranges between [0, 1].

The degree of coordination between the scale and speed of economic and social development and the level of ecosystem services in a composite ecosystem is a crucial factor affecting the development of urban agglomerations. Among the evaluation indicators, the economic subsystem is centered on the material and energy metabolic activities of human beings, which are mainly measured through the three dimensions of economic development, structure, and vitality (see Table 2). The social subsystem, on the other hand, is centered on human beings, with special emphasis on their basic needs, and mainly covers the three organic components of living standards, infrastructure, and public services. The natural subsystem is based on the ecosystems that support human existence. Utilizing the InVEST model, four key ecosystem services, water retention, soil conservation, carbon sequestration services, and habitat quality, were assessed. After standardizing the data for preprocessing, the weights of the indicators were determined using the entropy method.

Table 2. Assessment indicator system for urban composite ecosystem.

Target Level	System Level	Criterion Level	Indicator Level	Unit	Attribute	Weight
Composite Ecosystem	Economic Subsystem	Economic Development	Per Capita GDP	Yuan	+	0.1101
			Per Capita Disposable Income	Yuan	+	0.1107
			Per Capita Local Fiscal Revenue	Yuan	+	0.1100
			Per Capita Fixed Asset Investment	Ten thousand yuan	+	0.1100
		Economic Structure	The Proportion of the Secondary Sector in GDP	%	+	0.1121
			The Proportion of the Tertiary Sector in GDP	%	+	0.1123
		Economic Vitality	Fiscal Self-Sufficiency Ratio	%	+	0.1100
			Per Capita Retail Sales of Consumer Goods	Yuan per person	+	0.1100
			Total Social Labor Productivity	Yuan per person	+	0.1108
	Social Subsystem	Population Factors	Permanent Resident Population	people	+	0.0910
			Natural Population Growth Rate	%	+	0.0919
		Living Standards	Average Wages of Urban Non-profit Unit Employees	Yuan	+	0.0909
			Per Capita Net Income of Rural Residents	People per square kilometer	+	0.0910
			Registered Urban Unemployment Rate	%	−	0.0917
		Infrastructure	Per Capita Road Area	m²	+	0.0850
			International Internet Coverage Rate	%	+	0.0912
			Gas Penetration Rate	%	+	0.0925
		Public Services	Number of Teachers per Ten Thousand People	People	+	0.0900
			Number of Health Facilities per Ten Thousand People	Count	+	0.0900
			Comprehensive Social Health Insurance Coverage Rate	%	+	0.0900
	Natural Subsystem	Water Conservation	Annual Water Production	mm	+	0.2078
		Soil Conservation	Soil Conservation Quantity	$T \cdot hm^{-2} \cdot a^{-1}$	+	0.2301
		Carbon Sequestration Services	Carbon Storage per Unit Area	$t \cdot hm^{-2} \cdot a^{-1}$	+	0.3313
		Habitat Quality	Habitat Quality		+	0.4328

2.4. Methods for Assessing the Level of Development of Subsystems

2.4.1. Methodology for Assessing the Level of Economic and Social Development

The Composite Development Index (CDI) is often calculated from the standardized values and weights of the indicators [22], using the following formula.

$$L(a) = \sum_{j=1}^{J} w_j x_{tij} \quad (2)$$

$$T = \lambda L(1) + \mu L(2) + \eta L(3) \quad (3)$$

In this formula, a represents the subsystem; L(a) represents the comprehensive development index of the subsystem; j represents the evaluation index of each subsystem and J represents the number of evaluation indexes of the subsystem; t represents the year; i represents the region; w_j represents the weight of the indexes; x_{tij} represents the standardized value of the indexes; L(1), L(2), and L(3) represent the comprehensive development indexes of the economic subsystem, the social subsystem, and the ecological subsystem, respectively; and T represents the comprehensive development index of the composite system. λ, μ, η represent the degree of importance of the three subsystems to the development of the region. This paper posits that composite ecosystems represent an integrated ecological functional entity comprising economic, social, and natural factors, interconnected and interacting with each other. To facilitate a cross-sectional comparison of the actual conditions across various municipal subsystems, this study, while controlling for variables, assigns identical undetermined coefficients to each system, namely $\lambda = \mu = \eta = 1/3$, thereby enhancing analytical comparability.

2.4.2. Methodology for Evaluating the Level of Ecological Services of Natural Subsystems

1. Water conservation services

The formula for calculating water conservation services is based on the water yield module of the InVEST model. The model takes into account several factors such as topography, climate, soil layer thickness, and permeability [23]. The formula is as follows:

$$Y_{ij} = \left(1 - AET_{ij}/P_i\right) \times P_i \quad (4)$$

In the formula, Y_{ij} represents the annual water production of land use type j in grid i (mm); AET_{ij} represents the annual actual evapotranspiration of land use type j in grid i (mm); and P_i represents the average annual precipitation of grid i (mm).

2. Soil conservation services

The soil conservation model was calculated using a modified generalized soil loss equation. The formula is as follows:

$$SD = R \times K \times LS \times (1 - C \times P) \quad (5)$$

In the formula, SD represents soil retention ($t \cdot hm^{-2} \cdot a^{-1}$); R represents rainfall erosivity ($MJ \cdot mm \cdot hm^{-2} \cdot h^{-1} \cdot a^{-1}$); K represents soil erodibility ($t \cdot hm^2 \cdot h \cdot hm^{-2} \cdot MJ^{-1} \cdot mm^{-1}$); LS represents slope and slope length factors obtained by DEM; C represents vegetation cover and management factor; and P represents the engineering measures factor.

3. Carbon sequestration services

Carbon stocks are a measure of the capacity of terrestrial ecosystems to sequester carbon [24]. The formula is as follows:

$$C = C_{above} + C_{below} + C_{soil} + C_{dead} \quad (6)$$

The total carbon stock, C, represents the carbon stock per unit area in $t \cdot hm^{-2} \cdot a^{-1}$. C_{above} represents the carbon stock in above-ground material, C_{below} represents the carbon stock in below-ground material, C_{soil} represents the density of organic matter in the soil, and C_{dead} represents the carbon stock in dead leaves and leaves, all of which are in $t \cdot hm^{-2} \cdot a^{-1}$.

4. Habitat quality

The HQ (Habitat Quality) module of the InVEST model is based on the degree of sensitivity of each landscape type in the study area and the resulting habitat quality when it is threatened by external threats. Results ranged from 0 to 1, with values proportional to the level of habitat quality [25]. The formula is as follows:

$$Q_{xj} = H_j \left[1 - \frac{D_{xj}^Z}{D_{xj}^Z + k^Z} \right] \tag{7}$$

In the formula, Q_{xj} represents the habitat quality of a single raster x when the habitat or land use type is j; H_j represents the habitat suitability when the habitat or land use type is j; D_{xj} represents the weighted average of the threat levels of raster cell x when the habitat or land use type is j; k represents the half-saturation parameter, which is taken to be 1/2 of the maximum value of D_{xj}; and Z represents the normalization constant, which is taken to be 2.5.

$$D_{xj} = \sum_{r=1}^{R} \sum_{y=1}^{Y_r} \left(\frac{w_r}{\sum_{r=1}^{R} w_r} \right) r_y i_{rxy} \beta_x S_{jr} \tag{8}$$

$$i_{rxy} = 1 - \left(\frac{d_{xy}}{d_{r_{max}}} \right) \tag{9}$$

In the formula, D_{xj} represents the weighted average of the total threat level of grid x; r represents a specific threat factor; R represents all of the rasters on the raster layer of the threat factor r; Y_r represents the set of phases on the raster layer of the threat factor r; W_r represents the normalized threat weight, which ranges from 0 to 1; r_y represents the source of a raster y used to determine whether a raster y is a source of the threat factor r; i_{rxy} represents the distance function between the habitat class and the threat factor; β_x represents the level of accessibility of the threat source to grid x under the relevant state of environmental protection; and S_{jr} represents the sensitivity to the threat factor r when the habitat or land use type is j.

5. Integrated ecosystem services

The coefficient of variation method was used to construct the regional ecosystem services composite index, and the geometric mean method was used for the raster cells [26]. The formula is as follows:

$$ES_i = \frac{\sigma_{ik}}{x_{ik}} = \frac{1}{x_{ik}} \sqrt{\frac{1}{N} \sum_{k=1}^{N} (x_{ik} - \overline{x_{ik}})^2} \tag{10}$$

In the formula, ES_i represents the ecosystem services of the ith grid cell; σ_{ik} represents the original value of the kth ecosystem service on the ith grid cell in the region; x_{ik} represents the normalized value of the kth ecosystem service on the ith grid cell in the region; $\overline{x_{ik}}$ represents the average of the normalized value of the kth ecosystem service on the ith grid cell; and N is the main ecosystem service type.

2.4.3. Coupling Coordination Model

Coupling is a concept in physics used to describe the mutual influences, constraints, synergies, and amplifications between two or more systems or modes of motion through the exchange of matter, energy, and information [27]. The coupling coordination model is a widely-used analytical tool for assessing and analyzing the degree of interaction and coordinated development among different systems or subsystems. It views the object of study as one or more interrelated and interacting systems. Each system has its own structure and function, but they are interconnected through some form of interaction. The degree of coupling quantifies the degree of the ordering of the system as a whole and the strength of the interactions between the subsystems. The formula for calculating the coupling degree is as follows:

$$C = \left\{ U_1 \times U_2 \times U_3 / \left({(U_1 + U_2 + U_3)}/{3} \right)^3 \right\}^{\frac{1}{3}} \tag{11}$$

In the formula, C represents the degree of coupling and U represents the comprehensive development score of each subsystem.

$$D = \sqrt{C \times T} \tag{12}$$

In the formula, T represents the comprehensive development score of the composite ecosystem. Based on the results of related research [28,29], the degree of coordination D was categorized into 10 intervals (Table 3). Also, the lowest scoring of the three subsystems—economic, social, and ecological—was defined as the lagging subsystem. In order to harmonize the calculations, the values of the three coefficients to be determined were set to 1/3 in this study.

Table 3. Criteria for evaluating the level of coherence.

Serial Number	1	2	3	4	5	6	7	8	9	10
Main Class	Dysfunctional recession class				Transition class			Coordinated development class		
Coordination Degree	0–0.09	0.1–0.19	0.2–0.29	0.3–0.39	0.4–0.49	0.5–0.59	0.6–0.69	0.7–0.79	0.8–0.89	0.9–1.00
Coordination Degree Level	Extreme disorder	Severe disorder	Intermediate disorder	Mild disorder	On the verge of becoming disordered	Barely coordinated	Primary coordination	Intermediate coordination	Good coordination	High-quality coordination

3. Results

3.1. Spatio-Temporal Differentiation Characteristics of Economic–Social–Ecological Subsystem Development

3.1.1. Spatio-Temporal Differentiation Characteristics of Economic Subsystem Development

The economic subsystem of the central Yunnan urban agglomeration has exhibited a fluctuating yet overall upward growth trend over the past decade, where the score grows from 0.3825 in 2010 to 0.4463 in 2020, an increase of 16.7%. However, this growth has not been uniform across the region, with significant disparities observed among the cities within the agglomeration. Chuxiong Prefecture experienced the most rapid development within this period, recording an impressive growth rate of 118.1%. Despite this remarkable progress, it remains behind the other four cities and prefectures in terms of overall developmental level. Yuxi City had the next highest growth rate of 44.1%. In contrast, Qujing City experienced a decline in its economic development, with its subsystem score falling from 0.2554 in 2010 to 0.1770 in 2020. Meanwhile, both Kunming City and Honghe Prefecture experienced relatively modest growth rates, each below 15 percent. This variation in growth rates across different cities and prefectures highlights the uneven economic development within the central Yunnan urban agglomeration, reflecting a complex landscape of regional economic dynamics.

As shown in Figure 2, there was a tendency for the development gaps in the economic subsystems of the cities and states in the urban agglomerations to become smaller. In terms of the overall distribution pattern, Kunming City, as the provincial capital and only megacity, has become the high ground for the economic development of the city cluster. The urban agglomerations are characterized by a relatively homogeneous hierarchy of economic development, with an absence of fully developed sub-centers and a widespread presence of low-development regions. The current development model adopted by the Central Yunnan Urban Agglomeration includes schemes such as "one core city with four sub-centers, axially linked and interconnected" and "one core city with two sub-centers and six interconnections", aiming to create a green, livable, synergistic, efficient, open, and innovative urban agglomeration in Central Yunnan. While this model has facilitated rapid development in some central cities and regions, its implementation may result in slower development in certain cities or areas due to factors such as resource allocation and policy support, exacerbating inter-regional development imbalances.

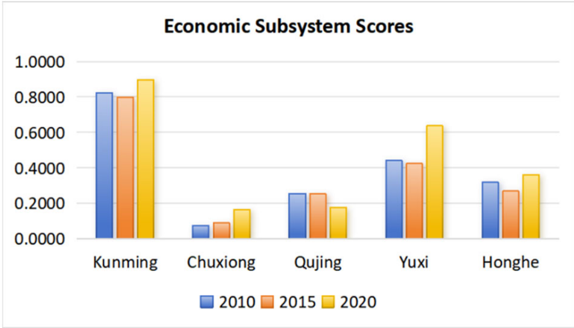

Figure 2. Economic subsystem scores for the central Yunnan urban agglomeration in 2010, 2015, and 2020.

Kunming City is going through a stage of polarized development, and its limited economic impact on neighboring areas contributes to uneven regional economic growth and an insufficient agglomeration effect. This scenario hinders the formation of a mutually reinforcing development pattern across the city cluster. Therefore, in order to make the whole city cluster develop in a long-term and healthy way, the economic development mode should choose balanced development instead of the leader-driven mode of Kunming City. This strategy is expected to evolve into a "pyramid-like" city scale structure within the cluster.

In addition, the rapid development of the central Yunnan urban agglomeration has been significantly influenced by the extensive export of local commodities and the overall domestic economic climate since 2010. Since the Belt and Road Initiative was proposed in 2013, Yunnan Province has become an active participant in the strategy. It has actively participated in the construction of the China-Central South Peninsula International Economic Cooperation Corridor and the Bangladesh-China-India-Myanmar Economic Corridor, and is building a radiation center for South Asia, Southeast Asia, and the Indian Ocean region with the support of the State. The central Yunnan urban agglomeration is well-positioned to become a key growth area in the Belt and Road Initiative, supported by multiple policies.

Nonetheless, the industrial structure of cities in Central Yunnan exhibits convergence, lacking clear industrial characteristics and competitiveness, which results in uneven resource allocation and an insufficient exploitation of development potential. The region faces challenges in transitioning from resource-dependent industries to strategic emerging sectors, with the evolution of an effective regional economic growth model still pending. In order to realize this transformation, central Yunnan must integrate more effectively into the vast domestic market and establish strong connections with South Asia, Southeast Asia, and the Indian Ocean Rim. By stimulating industrial innovation, open cooperation and regional influence, central Yunnan is poised to become a key driver for high-quality economic development in western China.

3.1.2. Spatio-Temporal Differentiation Characteristics of Social Subsystem Development

Robust infrastructure and public services play an important role in population agglomeration and economic growth. This principle is evident in the central Yunnan urban agglomeration, which had a score of 0.4043 in 2010 and 0.5094 in 2020, with an overall upward trend. Social subsystem scores increased in all cities and states except Qujing City. In particular, Chuxiong Prefecture grew from 0.1321 in 2010 to 0.4426 in 2020, marking an impressive increase of 235%. Both Kunming City and Yuxi City had growth rates of more than 15 percent. On the other hand, Honghe Prefecture shows a fluctuating pattern, initially showing an increase followed by a subsequent decrease.

As shown in Figure 3, in the central Yunnan urban agglomeration, the social subsystem shows less disparity across its municipalities and states compared to the economic subsystem. Regionally, Kunming City remains the highest scoring city, yet it still has considerable potential for enhancing its comprehensive urban service capacity. The other four cities and states in the agglomeration record roughly equivalent scores, each falling below 0.65. The problem of low levels of development in these areas, uneven hierarchical structures and inadequate regional development remains significant. The inadequacy and uneven distribution of infrastructure impede the development of certain regions, affecting interconnectivity and resource sharing within urban agglomerations. The quality of urban public service facilities correlates positively with the size of the urban population; smaller cities or rural areas may exhibit relatively weaker public service facilities. Improvements in educational quality within the region have a catalytic effect on nurturing excellent human resources, thereby enriching the local talent pool. This enrichment is key to elevating the quality of the workforce in the urban agglomeration and facilitating the efficient movement of economic factors. However, due to various limitations such as geographical location, transportation infrastructure, economic base, and limited innovation capabilities, the central Yunnan urban agglomeration still lags behind other Chinese urban clusters in socio-economic development. Therefore, upgrading the spatial aggregation and overall capacity of this city cluster is a critical objective. The implementation of a "strong provincial capitals" strategy can fully utilize the influence and driving effect of provincial capitals. Strengthening the synergistic development and integration process between Kunming City and its neighboring counties (including cities and districts) is pivotal. This approach aims to establish a city cluster characterized by concentrated resources, complementary advantages, efficient transportation, and elevated openness. Such strategic developments can propel the central Yunnan urban agglomeration towards a more dynamic and integrated urban future.

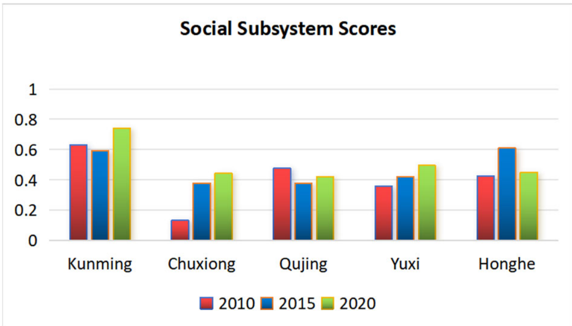

Figure 3. Social subsystem scores for the central Yunnan urban agglomeration in 2010, 2015, and 2020.

3.1.3. Spatio-Temporal Differentiation Characteristics of Natural Subsystem Development

(i). Water conservation services

As shown in Figure 4, temporally, the average multi-year unit water yield of the urban agglomeration in central Yunnan was 8438.134 mm. Water production has gradually increased overall, showing a fluctuating upward trend. Among them, the peak in water production was observed in 2015, while 2010 marked the lowest value in this period. Spatially, the amount of water production in the urban agglomeration of central Yunnan gradually increases from southwest to northeast. Moreover, a significant spatial differentiation pattern emerged, with higher water production typically found in upstream areas compared to downstream areas. This spatial distribution indicates a clear and distinct gradient in water yield across the region, highlighting a clear pattern of spatial differentiation.

In terms of the influencing mechanism, the water conservation capacity of the urban agglomeration in central Yunnan is affected by a combination of factors, with topographic relief being a significant contributor. Topographic relief is an important factor, as the flow of rivers on the surface gradually slows down due to changes in topography. This results in a longer time for the soil to absorb water after the runoff passes over the surface, increasing the amount of time the soil is in contact with the water, which promotes water production and water-holding capacity. In the southern part of the Yuanjiang River Basin, its forest area is extensive and vertically structured. The degree of high-density vegetation cover fills in the difference between the widely distributed evergreen broadleaf and deciduous broadleaf forests in terms of their ability to contain rice soils, resulting in a high level of water retention. In the central part of the study area, the widespread distribution of sclerophyllous broadleaf forests and scrubs together serve to trap rainwater. It also separates the forest from urban settlements and rural cultivation areas, effectively reducing the negative impact of human activities on forested areas [30]. Although the north-eastern cultivated area has a slightly lower water yield and high agricultural activity, it is highly urbanized and has a lower water-holding capacity. However, in recent years, a variety of soil and water conservation measures have been implemented to enhance the protection of the top soil layer of cultivated land, which provides abundant organic matter, and thus, the water-holding capacity of the region has increased in 2020. Overall, areas with high water-holding capacity are primarily located in the northeastern cultivated lands and the southern forests, while the low-holding sites are mainly located in the central built-up area and the northwestern woodland-scrub complex. A notable case is the Panlong River Basin within Kunming City, where water retention is more limited. This limitation is because the area has less soil cover in the lower bedding, lower vegetation cover, and most of the area has been replaced by urban construction land, which is unable to effectively intercept and infiltrate precipitation. These findings highlight the complex and diverse dynamics of water conservation in the central Yunnan urban agglomeration and are important for customizing regional water management strategies.

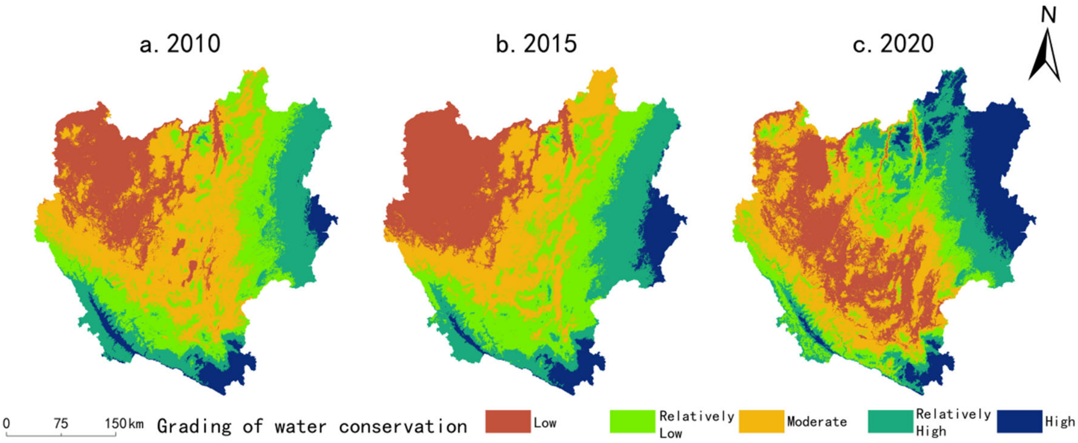

Figure 4. Grading of water conservation services in the central Yunnan urban agglomeration in 2010, 2015, 2020.

(ii). Soil conservation services

As shown in Figure 5, in terms of temporal change, between 2010 and 2020, the overall soil conservation function showed an increasing and then decreasing trend. The lowest soil retention was in 2010, with an average as low as 7.3×109 tons, and the highest was in 2015, with an average as high as 9.8×109 tons. This fluctuation is likely attributable to the rapid urbanization process during this period. In terms of spatial distribution, the soil retention in the central Yunnan urban agglomeration in 2010, 2015, and 2020 showed the characteristic of being high in the southwest and low in the central and northern parts of the country. The areas with the highest values were predominantly in the southwestern and northern parts of the study area, characterized by dense woodland coverage, higher altitudes, steep slopes, and favorable vegetation conditions. The broad-leaved evergreen and deciduous forests in these regions effectively reduce soil erosion. In contrast, the low value areas were clustered mainly in the central urban construction sites and rural farming areas. These regions are generally flatter and lower in elevation, with frequent human activity impacting them. Despite the implementation of relevant measures, actual soil erosion and loss are difficult to avoid, and the capacity for soil and water conservation has declined significantly.

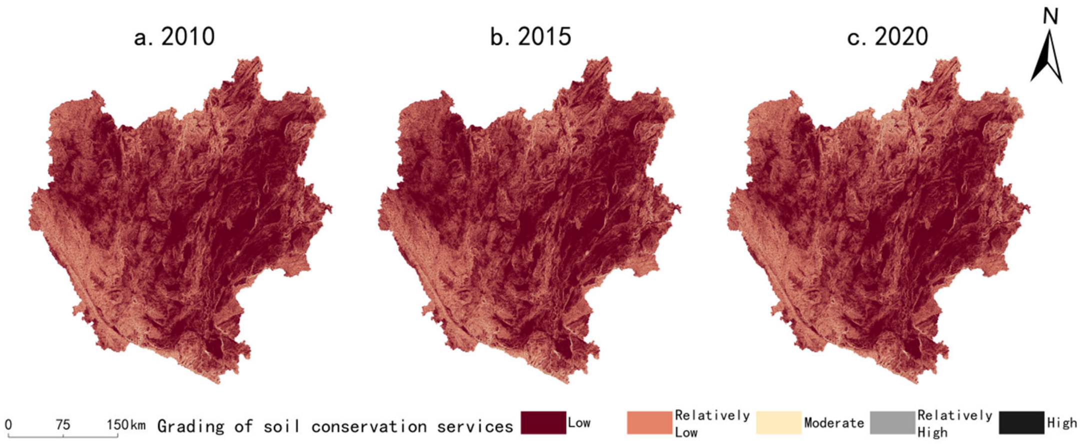

Figure 5. Grading of soil conservation services in the central Yunnan urban agglomeration in 2010, 2015, 2020.

In terms of the influencing mechanism, the decline in soil conservation function observed between 2015 and 2020 in the central Yunnan urban agglomeration is primarily attributed to the impacts of rapid urbanization. This includes factors such as increasing population density, the expansion of construction areas, the growth of bare land zones, and a notable reduction in wetland spaces. Among the various land use and cover types, soil retention is significantly higher in forested land than in other types; croplands and grasslands also contribute positively to soil conservation. Focusing on soil erosion, both the total volume and per unit area soil loss are considerably higher on bare lands compared to other land types. Bare ground is more susceptible to rainfall and other physical erosion because it lacks the buffering effect of cover such as vegetation and lawns. As a result, its soil loss is also greater than other land types with vegetative cover, which contributes to the lower soil retention in 2010.

(iii). Carbon sequestration services

As shown in Figure 6, in terms of temporal changes, the carbon stock per unit area of the urban agglomeration in central Yunnan was 36,935.965 t/km^2, 36,916.427 t/km^2, and 36,694.762 t/km^2 in 2010, 2015, and 2020, respectively, which remained relatively stable. In terms of spatial distribution, the pattern of carbon storage capacity during this period consistently exhibited a trend of being "higher in the surrounding areas and lower in the central region". The spatial distribution of carbon storage remained stable throughout the study period, with no significant shifts or alterations observed. The disparity in carbon stock between areas with high and low values was not pronounced. The high-value areas were mainly located in Yuxi, Chuxiong Prefecture, and Qujing City, while the low-value areas were mainly located in Kunming City and Honghe Prefecture.

In terms of the impact mechanism, between 2010 and 2015, the central Yunnan urban agglomeration witnessed an expansion in built-up land area, but concurrently, initiatives like farmland reforestation led to an increase in forested areas, resulting in relatively stable carbon stocks. Carbon sequestration was richer in forested land and cropland, and very low in bare land, built-up land, and watersheds. Areas with limited woodland and grassland, particularly cultivated lands, have a relatively weak absorptive capacity of carbon sinks and are unable to fully absorb the emitted carbon, resulting in partial carbon loss. From 2015 to 2020, rapid urbanization, modernization, industrialization, and socio-economic development contributed to a decrease in forested land, slightly diminishing the region's carbon sequestration capacity. The central area, particularly urban construction land in Kunming City and its environs with lesser forest and grassland coverage, presents an extensive low carbon storage area. Conversely, the peripheral areas of municipalities, further from urban and rural influences and benefiting from a more favorable natural environment, exhibited higher carbon stocks. For example, carbon stocks were higher in the southwestern region, mainly because of better vegetation cover and relatively less human intervention, and carbon emitted from carbon sources can largely be absorbed and fixed. This indicates the significant impact of vegetation condition and human activities on carbon stocks.

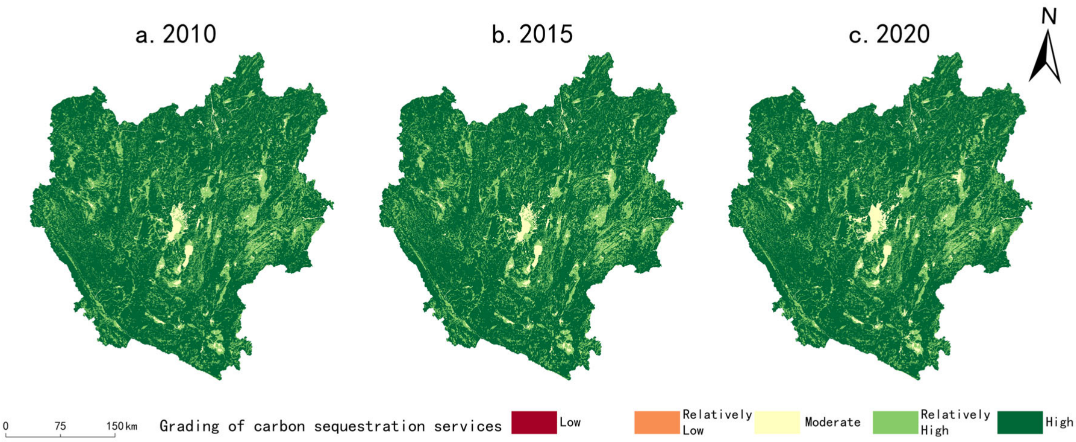

Figure 6. Grading of carbon sequestration services in the central Yunnan urban agglomeration in 2010, 2015 and 2020.

(iv). Habitat quality

As shown in Figure 7, in terms of temporal changes, the habitat quality index of the central Yunnan urban agglomeration declined slightly between 2010 and 2020, with an average value of 0.00561. Overall, habitat quality remained moderately high but declined by 7.9%. Notably, the period between 2015 and 2020 saw a more pronounced decline, at 5.7%. In terms of spatial distribution, the habitat quality coefficient of this urban agglomeration showed a spatial distribution characteristic of high in the southwest, high in the northeast, and low in the central region. The central area's limited natural vegetation cover, coupled with its proximity to urban and rural settlements characterized by intense human activity, contributes to its comparatively poorer habitat quality. In contrast, the area of dense woodland to the southwest has excellent ecological indicators for the natural growth of all types of organisms. Additionally, efforts to conserve woodlands and grasslands in the eastern and northern regions have positively influenced habitat quality levels in these areas.

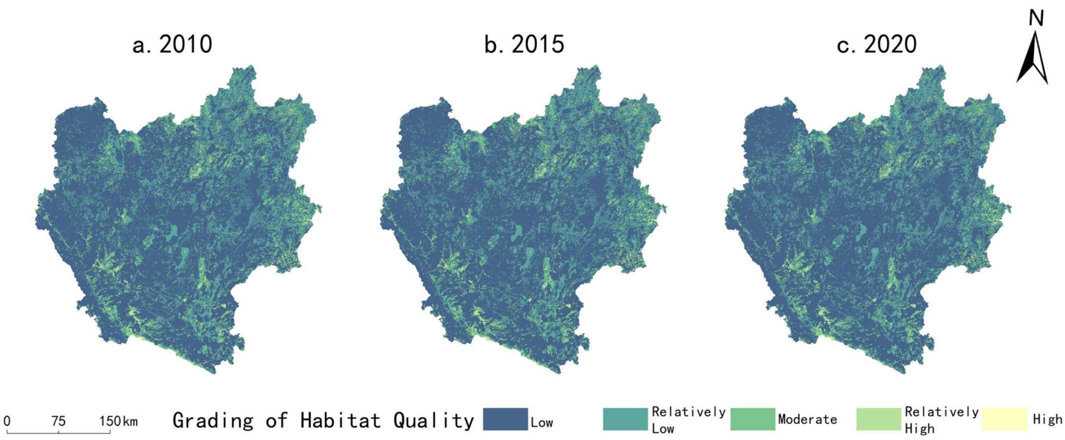

Figure 7. Grading of habitat quality in the central Yunnan urban agglomeration in 2010, 2015, 2020.

In terms of impact mechanisms, between 2010 and 2020, the level of the destruction of natural habitats increased in watershed areas with intensive human activities. Reduced regional vegetation cover, the increased fragmentation of terrain, and elevated levels of soil erosion have led to a decline in habitat conditions in the central region. Conversely, with the construction of forestry reserves and the widespread implementation of policies such as those for converting farmland back into forests, key nature reserves have been better maintained. The low level of anthropogenic disturbance has led to improved habitat conditions in the southern woodlands, contributing to an overall positive shift in habitat quality. Among the various land types assessed, woodland and grassland performed well on various environmental indicators. While cropland fell slightly short in terms of the habitat quality index when compared to woodlands and grasslands, it still maintained a moderate rating and played an essential role in the ecosystem's functioning through daily crop-related activities. Due to the relatively low percentage of watershed area in the watershed, the corresponding habitat quality index is significantly lower than the other three. Therefore, the focus should be on the protection and restoration of woodlands and grasslands, as these efforts have the potential to significantly enhance the overall habitat quality within the studied watershed.

(v). Integrated ecosystem services

In order to delineate the importance level of ecosystem service functions in the central Yunnan urban agglomeration, the results of InVEST modeling were normalized and spatially quantified using ArcGIS and the rating of integrated ecosystem services for 2010, 2015, and 2020.The results are shown in Figure 8.

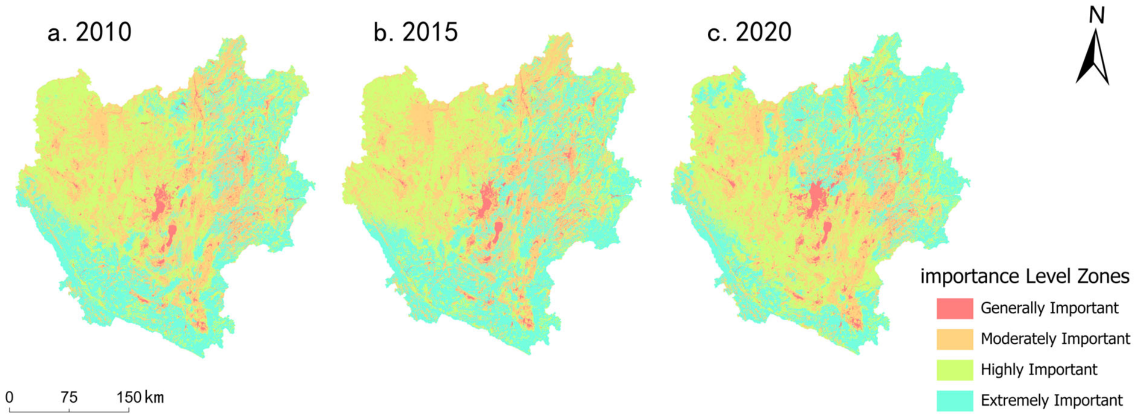

Figure 8. Ecosystem service function importance level zones.

By observing the spatial distribution characteristics of each sub-area as depicted in Figure 8, it can be seen that the zone of extremely important ecosystem service functions is mainly distributed in the southwestern periphery and northeastern region of the study area. These areas are characterized by extensive forested and grassland areas, have a high abundant vegetation cover that serves as an effective carbon sink, and a source of water retention. At the same time, efforts to protect natural resources in these regions should be strengthened. Existing ecological protection measures are utilized to strengthen the supply capacity of ecosystem services in order to eliminate behaviors such as the deforestation and pollution of water sources, which in turn serve as an ecological barrier to protect the ecosystem of the Yunnan-Guizhou Plateau.

The highly important and moderately important areas are primarily situated in the northwestern and southwestern portions of the study area, characterized primarily by woodland, cropland, and building land. Within these zones, it is imperative to implement strict measures for environmental pollution control. Furthermore, it is necessary to exercise strict control over the expansion of urban development to mitigate its encroachment on cropland, forested areas, and other vital ecological lands. In addition, it is necessary to improve the utilization rate of construction land development per unit area, realize intensive and economical land use, and reduce the impact of unreasonable human activities on the region [31].

The generally important areas are primarily concentrated within the central region of the study area, characterized predominantly by cropland, construction land, and water bodies. These regions exhibit low vegetation cover and experience relatively high levels of anthropogenic disturbances. They represent pivotal zones for pollution prevention and control. In addition to the strict regulation of urban expansion and the enhancement of efficient construction land utilization, it is imperative to extend protective measures to safeguard water and wetland ecosystems. There is a need to effectively protect water sources and quality and to reduce the disturbance of these areas by human activities.

The construction of China's ecological and environmental protection system still has some urgent shortcomings that need to be addressed. For instance, the constraint force of source prevention has not been fully exerted, and further efforts are needed to enhance the connection between pollutant discharge permits and other environmental management systems in the process control. Moreover, the responsibility for ecological and environmental protection is not yet sufficiently clear.

In the future, while continuously strengthening institutional enforcement, the construction of the natural environmental protection system will also focus on expanding and extending forward, encompassing various aspects such as economic processes, production methods, and decision-making behaviors, beyond the management of pollution sources. Emphasizing source prevention as the fundamental strategy for pollution control, efforts will be made to foster spatial patterns, industrial structures, production methods, and lifestyles conducive to environmental protection. Addressing structural and layout-related ecological environmental pollution issues, China has explored and established spatial control systems, such as the ecological protection red line, that are adaptable to the national conditions of resources and the environment. Based on the zoning of key functional areas, spatial ecological assessments are conducted to delineate the "three zones and three lines" (urban, agricultural, and ecological spaces, ecological protection red lines, permanent basic farmland protection red lines, and urban development boundaries), and negative lists for environmental access, thus achieving effective control over ecologically significant areas through red line management.

3.2. Coupling and Coordination Relationships in Composite Ecosystems

3.2.1. Status of Development of Coupling in Composite Ecosystems

The composite ecosystem coupling within the central Yunnan urban agglomeration was 0.9418 in 2010 and exhibited an increase to 0.9492 by 2020. Both values indicate a high level of coupling within the system. Furthermore, as shown in Table 4, the coupling degree values of the composite ecosystems in each prefecture and city are all greater than 0.9. This finding underscores the consistent developmental trajectory of the three subsystems—economy, society, and nature—within the Central Yunnan Urban Agglomeration, highlighting their intricate interrelationships and interactions. However, it is noteworthy that the composite ecosystem coupling for the year 2020 exhibited a slight decline, recording a value of 0.9412, compared to the value for 2010. This decline suggests variations in the developmental pace of the subsystems, contributing to a minor reduction in the overall coherence of the composite system.

Table 4. The coupling degree of composite ecosystems in various prefectures and cities in 2010, 2015, and 2020.

Coupling Degree	2010	2015	2020
Kunming City	0.9368	0.9426	0.9264
Chuxiong Prefecture	0.8145	0.8362	0.9199
Yuxi City	0.9958	0.9983	0.9729
Qujing City	0.9687	0.9833	0.9323
Honghe Prefecture	0.9929	0.9453	0.9947

The coupled developmental changes in the relationship between the economy, society, and nature are shown in Table 5. Changes in the two-by-two relationships of the three subsystems were largely consistent with the trend of changes in the coupling of the composite ecosystem. Between 2010 and 2015, the economy and nature subsystems displayed the least coupling, signifying a decline in harmony within the interplay among the economy, society, and nature. From 2015 to 2020, in the process of a general increase in the harmonization of economic, social, and ecological relations, the degree of the harmonization of the coupling between the economy and society and between society and nature was higher than that of the coupling between the economy and nature.

Table 5. The coupling degree between subsystems in various prefectures and cities in 2010, 2015, and 2020.

	2010			2015			2020		
Subsystem Pairwise Coupling Degree	**Economic–Social**	**Social–Natural**	**Economic–Natural**	**Economic–Social**	**Social–Natural**	**Economic–Natural**	**Economic–Social**	**Social–Natural**	**Economic–Natural**
Kunming City	0.9913	0.9524	0.8702	0.9889	0.9630	0.8728	0.9954	0.9317	0.8748
Chuxiong Prefecture	0.9600	0.8928	0.8841	0.7832	0.9984	0.9184	0.8859	0.9937	0.9029
Yuxi City	0.9943	0.9997	0.8921	0.9999	0.9982	0.8898	0.9921	0.9868	0.8823
Qujing City	0.9534	0.9922	0.8977	0.9803	0.9999	0.8949	0.9133	0.9997	0.9200
Honghe Prefecture	0.9896	0.9986	0.8967	0.9213	0.9754	0.9137	0.9938	0.9946	0.8861

3.2.2. Characteristics of Spatial and Temporal Variability in Coordination in Composite Ecosystems

The coupling degree can measure the orderliness of the overall structure of the system and the strength of the interactions between subsystems, but it cannot fully reveal the nature of the coupling. Therefore, the degree of coordination is introduced as a comprehensive indicator to assess the coupling relationships and developmental levels more comprehensively.

As shown in Figure 9, in 2010, the mean value of the coupling coordination degree within the composite ecosystem of the central Yunnan urban agglomeration stood at 0.5934. By 2020, this figure had risen to 0.6398, marking an overall increase of 7.82%. Notably, according to Table 6, all five cities and prefectures displayed coupling harmonization within the range of 0.5 to 0.8 in 2020. Specifically, Chuxiong Prefecture and Qujing City exhibited lower levels of harmonization, while Yuxi and Honghe Prefecture attained barely coordinated levels. Kunming City stood out as the sole region achieving an intermediate level of coordination.

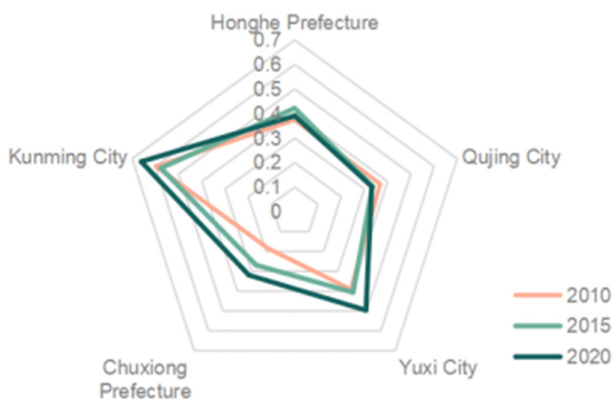

Figure 9. Degree of coupling coordination among states and cities in the central Yunnan urban agglomeration.

Table 6. Coupling coordination of the central Yunnan urban agglomeration in 2020.

Region	Coordination Degree	Coordination Degree Level	Lagging Subsystem
Kunming City City	0.7824	Intermediate coordination	Natural Subsystem
Chuxiong Prefecture Prefecture	0.5419	Barely coordination	Economic Subsystem
Yuxi City	0.6947	Primary coordination	Natural Subsystem
Qujing City City	0.5564	Barely coordination	Economic Subsystem
Honghe Prefecture Prefecture	0.6235	Primary coordination	Economic Subsystem

As the main core area for the development of the urban agglomeration, Kunming City has a robust industrial base and dense population distribution. It plays a pivotal role in driving the urbanization, industrialization, informatization, and innovative development of the central Yunnan urban agglomeration. However, the high-density development pattern within Kunming City's central city has engendered a range of complex challenges, including traffic congestion, environmental degradation, the concentration of industries, and the depletion of limited land resources. Moreover, the expansion of construction land and population growth have led to a significant reduction in arable land. These problems have triggered the "barrel effect" of the sustainable development resource system in central Yunnan, adversely impacting the overall sustainability of the urban agglomeration. While the economic and social subsystems have driven high levels of composite ecological coupling coordination within Kunming City, it is crucial to address the imbalance between rapid economic growth and ecological preservation in the region. Future development strategies should prioritize green ecological principles, optimize the energy structure, and underscore the protection and management of the ecological environment. Such measures are essential for promoting the coordinated development of the economy, society, and ecology.

Yuxi City, second only to Kunming City in terms of coordination, had a similar ecological subsystem with Kunming City. It showed that the traditional urbanization development model faced increasing pressure and contradictions during the urban development process. Yuxi concentrates the ecologically sensitive areas of three lakes and one sea, and assumes important ecosystem service functions. Consequently, future efforts should strictly adhere to regulations aimed at safeguarding these sensitive areas, such as Fuxian Lake, Xingyun Lake, Qilu Lake, and Yangzong Sea [32]. These regulations should prohibit the placement of highly polluting industrial enterprises within the watershed and impose strict limits on Anning City and the construction of new industrial parks. The central Yunnan urban agglomeration primarily exhibited two types of coordination degrees: 'barely coordinated' and 'primary coordination'. Its internal structure and external scale are an important reflection of the overall condition and degree of development of the region. Among the barely coordinated and primary coordinated regions, the combined development scores of the economic and ecological subsystems are generally similar, except for Chuxiong Prefecture which possessed a lower economic development score. In all regions, the ecological subsystem consistently scored the lowest. In Chuxiong Prefecture and Qujing City, the towns experienced relatively lower economic development and quality of life, with limited resource utilization intensity. Consequently, economic and social development have not yet significantly impacted the ecological environment in these areas, resulting in relatively higher ecological subsystem scores. In future development endeavors, these regions should leverage their ecological and cultural advantages to stimulate the growth of green industries and enhance collaboration with neighboring regions. Such efforts will help bridge the economic development gap and elevate the overall urban development standard.

Honghe Prefecture is situated adjacent to the national border, with a strategic position for facilitating border-related development and trade. In the future, the development of border trade should be actively promoted and its integration into the national external development strategy should be accelerated [33].

A more in-depth analysis of subsystem status and coupling reveals that the primary factor influencing the degree of coordination was the relatively low score in integrated development, particularly within the economic and ecological subsystems. Consequently, achieving high-quality urban agglomeration development hinges on several key strategies. In terms of economic development, it is imperative to establish a robust and regionally distinctive industrial platform while enhancing the overall capacity of our cities. Additionally, guiding the systematic migration of the agricultural population is crucial. Apart from Kunming City, the core city, there remains a big disparity between the level of economic and social development in other cities within the urban agglomeration and that of more developed urban agglomerations in China. Thus, concerted efforts are still required to bridge this gap by improving infrastructure and public service levels.

4. Discussion

4.1. Discussion

Ecosystems serve as the foundation for economic development and are essential for societal survival. Given the regional disparities in natural conditions and resource endowments, human activities must be carried out within the natural carrying capacity to ensure sustainability. According to the theory of coupled coordination, the three subsystems—economic, social, and ecological—influence and constrain each other. The ecological coupling relationships and interaction mechanisms among these subsystems across dimensions like time, space, quantity, structure, and order determine the development and succession direction of the composite ecosystem. The development and synergistic evolutionary characteristics of subsystems within composite ecosystems are currently focal points in the realm of human-land relationship research. The mainstream research methods currently include regression analysis [34], input–output models [35], system dynamics models [36], and coupling coordination models [37]. Based on system theory, coupling coordination models regard the object of study as one or more interrelated and interacting systems. They can assess the overall performance of systems through appropriate indicators, making them suitable for studying dynamic relationships among multiple systems, such as the economy, society, and environment. In computing the scores of the economic and social subsystems in this study, international standards, national averages, and reference values from planning documents were utilized instead of the extreme values typically employed in traditional methods, thereby enhancing the objectivity of the results. The Central Yunnan Urban Agglomeration, situated on the southwestern border of China, exhibits an overall lower level of development compared to most urban agglomerations in the country, with economic and social development scores generally lower apart from Kunming city. The key to assessing coordination lies in exploring the external scale and internal orderliness of the composite system. Coupling analysis and the identification of lagging subsystems are essential preliminary tasks. In conducting the coupling analysis of the human–environmental regional system, this study substituted per capita indicators for aggregate indicators to better highlight development quality and effectiveness. Furthermore, situated in the Yungui Plateau region, characterized by complex terrain and diverse ecosystems with significant differences in ecosystem service values, this study utilized multi-source data and conducted analyses based on raster units to emphasize the natural characteristics of the ecosystem.

4.2. Future Prospects

Based on the findings, this study makes the following recommendations: As an important economic center in southwest China, the central Yunnan urban agglomeration should increase the construction of agriculture and industry, promote the development of the service industry, increase the proportion of tertiary industry, and promote the optimization of industrial structure. In areas where the economic subsystems are lagging, emphasis should be placed on advancing industrial transformation and upgrading. This can be achieved by bolstering scientific research funding, promoting the smart transformation of traditional industries, and nurturing specialized high-technology sectors, thereby stimulating regional economic growth [38]. In addition, given the region's unique geological characteristics and pronounced seasonal rainfall, extreme disasters are frequent. In the process of rational city planning for economic development, the path for the synergistic development of multiple ecosystem services should be explored in light of changes in local climatic conditions in order to reduce losses caused by disasters. In ecologically fragile areas, it is imperative to reduce human economic activities. Additionally, we must elevate local residents' awareness of soil and water conservation and environmental protection. These efforts are vital for achieving the dual objectives of ecological preservation and high-quality development within the central Yunnan urban agglomeration.

The composite ecological system of a region is a diverse and complex entity. Building upon relevant research, this study has constructed an assessment framework comprising economic development, economic structure, economic vitality, demographic factors, living standards, infrastructure, public services, water conservation, soil retention, carbon sequestration, oxygen release, and habitat quality. However, despite this comprehensive framework, the connotations of evaluation indicators may still lack systemic comprehensiveness as development shifts towards a human-centered, resource-efficient, and environmentally friendly approach. Subsequent research will continue to supplement and refine these indicators. Focusing on the five municipalities of the Central Yunnan Urban Agglomeration as the primary research units, while providing guidance on macro-regional development, this study cannot deeply understand the development status at smaller levels such as counties and towns. Additionally, due to missing data, linear interpolation was employed to complete some missing data, introducing potential errors that may impact the results of empirical analysis. Future research should explore methods to overcome constraints in obtaining original data, consider micro-scale regionalization, and conduct related studies at the district and county levels to provide more granular insights into development dynamics.

5. Conclusions

(i). From 2010 to 2020, the economic subsystem score of the Central Yunnan Urban Agglomeration increased from 0.3825 in 2010 to 0.4463 in 2020, representing a growth rate of 16.7%. Similarly, the social subsystem score increased from 0.4043 in 2010 to 0.5094 in 2020, indicating an overall upward trend for both subsystems. In terms of spatial distribution, they displayed a pattern of outward expansion, radiating from the core city of Kunming City. Nevertheless, low-level areas still exist in large numbers, especially in Chuxiong Prefecture. The overall level of the social subsystem is better than that of the economic subsystem, but the lack of sub-centers and the uneven development of the municipalities and states are more evident.

(ii). From 2010 to 2020, water conservation and soil conservation services in the central Yunnan urban agglomeration experienced fluctuating trends of increases and then decreases. Carbon sequestration services remained relatively stable, whereas habitat quality services showed a declining trend. The areas of extremely high importance for ecosystem service functions were primarily distributed in the southwest edge and northeast region of the study area, while areas of high and moderate importance were mainly distributed in the northwest and southwest regions, respectively. Areas of general importance were primarily located in the central region of the study area. In the future, source prevention should be prioritized as the fundamental strategy for natural resource conservation.

(iii). From 2010 to 2020, the coupling degree of the composite ecosystem within the central Yunnan urban agglomeration consistently exceeded 0.8, signifying a high level of overall coupling. The interactions between economic, social, and ecological subsystems are strong and significant. Changes in the two-by-two relationships of the three subsystems were largely consistent with the trend of changes in the coupling of the composite ecosystem.

(iv). Between 2010 and 2020, the mean coupling coordination of the composite ecosystem in the Central Yunnan Urban Agglomeration increased from 0.5934 in 2010 to 0.6398 in 2020, indicating an overall upward trend. Only Kunming City achieved an intermediate barely coordinated status, and barely coordinated and primary coordinated are the main types of urban agglomeration coordination. The lagging subsystems in each municipality were mainly the economic and ecological subsystems.

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Informed Consent Statement: This study did not involve humans, so we chose not to include this statement.

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