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Analysis of Spatial and Temporal Pattern Evolution and Decoupling Relationships of Land Use Functions Based on Ecological Protection and High-Quality Development: A Case Study of the Yellow River Basin, China

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Abstract: With rapid industrialization and urbanization, the contradiction between the human exploitation of land production and living functions and natural ecosystem service functions has intensified. The issues of how to coordinate the exploitation and conservation functions of land and guide the rational distribution of human activities have become important for global sustainable development, especially considering the realization that multifunctional land use is an effective way to relieve land pressure and improve land use efficiency, that land multifunction has significant spatio-temporal heterogeneity, and that there is a mutual promotion and stress relationship between multifunctional land use. However, few existing studies have discussed the decoupling relationship among land use functions. In this study, a system of 10 sub-functions and 25 indicators was established based on the production function (PDF), living function (LVF), and ecological function (ELF) for 59 cities in the Yellow River Basin (YRB). There are both subjective and objective procedures employed to determine the weights, while an exploratory spatial data analysis is used to analyze the time-based and territorial changes in various functions of land use in the study area from 2000 to 2020. The decoupling relationship between the three functions is detected utilizing the theoretical foundation of the decoupling analysis. The results show that land use is multifunctional, LUFs develop unevenly, and their spatial distribution varies substantially. The results of the decoupling analysis demonstrate that the predominant types of correlations among the land use ELF and PDF and LVF over the research period are strong decoupling and strong negative decoupling correlations, with the former being a dilemma and the latter being a sustainable type of development.

Keywords: LUFs; ecological–production–living functions; decoupling relationship; Yellow River Basin

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1. Introduction

Over the past decades, China's economic output-oriented land space development model has exacerbated the contradictions among cities, agriculture, and ecology [1,2], generating a series of derivative problems, such as the unbalanced development of land space, overconsumption of resources, serious deterioration of the ecological environment, and uncoordinated development [3,4]. With the proposal of unified territorial spatial planning in China, optimizing and coordinating the spatial pattern of agriculture, towns, and ecology have become the core content of the sustainable development of territorial space [5]. The essence of homeland space is the interactive functional space determined by LUFs [6]. As the basis of land resource allocation and homeland spatial planning [7,8], revealing the evolution and interaction of LUFs is of great significance for optimizing and controlling homeland space.

Land use runs through the whole development process of human society [9]. Resources from the land are not only used to produce components of production such as water [10], food, as well as other necessities for human survival [11], but also are important carriers for various economic and social activities of human beings, and also have ecological environment elements such as soil, hydrology, climate, and vegetation, which deter-mine the multiple functional attributes of land use, i.e., [12–15], multifunctional land use.

Originating from agricultural multifunctionality, LUFs encompass the economic, social, and environmental dimensions of regional sustainable development, which refers to the ability to provide private and public goods or services through diversified land use [16,17], and typically include economic, social, and environmental functions [18]. In recent years, research on LUFs has been more extensive, focusing on the conceptual and theoretical framework of LUFs [17], the construction of the indicator system [19], spatial identification [8], spatio-temporal changes [16,17], and other aspects, as well as the spatio-temporal evolution of LUFs [20,21], influencing factors [22,23], trade-off analysis, and sustainable land management [24,25]. Existing studies mainly focus on a single province or city as the basic research scope, with relatively few studies at the watershed scale; in the determination of LUFs, the differences in functions between regions are not taken into account; and the judgment of the coordination of LUFs mostly relies on the coupled coordination degree model, which is too homogeneous in its approach. We argue that the scale of the land use framework is similar to that of ecosystem services [26], with stakeholders at different scales focusing on different priorities. At small scales, more attention is paid to the economic and social functions of land use, such as economic output and employment support [27]; at large scales, more attention is paid to major regional functions, such as the ecological barrier function of the Yunnan–Guizhou Plateau and the food production function of the Jianghan Plain [28]. Therefore, in a large region such as the Yellow River Basin (YRB), we should use a higher-level administrative unit as the evaluation unit to study the impacts of land use change.

Existing studies have mainly focused on the assessment of land use functions and their multifunctional characteristics [8,19], or the trade-off relationship between different types of land use functions and their influence mechanisms [24,25]. The mechanism of inter-functionality of land use has not yet been finalized., and in addition to the relationship between trade-offs and synergies, there may also be a "decoupling" relationship between the multifunctionality of land use in the Yellow River Basin in view of the large geographic and developmental differences between different regions in the upper, middle, and lower reaches of the Basin. As a measure of the coupling degree between human activities and resources and the environment, decoupling theory has attracted much attention worldwide, and is now mainly used to measure the degree of decoupling between energy, environment, water resources, etc., and economic development [29–34]. There are not many studies on the decoupling relationship between the multifunctionality of land use; the decoupling analysis method can be used to analyze the response relationship between two or more elements, which can effectively reveal the degree of influence between the production, living, and ecological functions of land use, and according to the different state of decoupling, we can distinguish the development process and evolution trend of regional land use. Therefore, we want to identify the decoupling relationship between the complex and diverse land use functions in the YRB and highlight the interaction mechanism of land use functions and regional heterogeneity.

In light of this, the primary goals of this work are as follows:

(1) To develop a research framework on the assessment of LUMF and the relationship between different functions, taking into account temporal and regional effects [35,36].
(2) To construct a comprehensive evaluation index system with a large scale and multiple indicators to evaluate LUMF [37].
(3) To examine spatial disparities and the emergence of multifunctional land use across time.
(4) To analyze the decoupling relationship between the PDF, LVF, and ELF in a long time series [38].

(5) Analysing the decoupling of ELF from PDF and LVF over long time series to decipher the evolution of the decoupling status of land use functions in each region.
(6) To propose governance proposals and policy recommendations based on the results of land use function research [18].

2. Methods

2.1. Research Framework

Land usage in China is facing problems of disorderly development, structural imbalance, functional degradation, and ecological environment destruction in the midst of a major urbanization process. Through making wise use of the land, different controls on agricultural, urban, and ecological spaces are carried out so as to maximize the land use function.

Figure 1 displays the theoretical structure used in this study. Different units in the study area have different natural resource endowments, socio-economic conditions, and other factor inputs, which are differentiated into agricultural production, non-agricultural production, livelihood security, and ecological land use services. The various functions are interdependent and also influence each other. The PDF provides agricultural, economic, and transportation products and services for the LVF; the LVF provides motivation for the PDF [25], but excessive demand can impose restrictions on the PDF; the ELF provides natural and physical conditions for the PDF and LVF, but the development of the LVF and PDF may lead to resource depletion and damage to the ecological structure [39]. A comprehensive evaluation using multi-source data from multiple years is combined with an exploratory spatial analysis to summarize the multifunctional dynamic changes and spatial differentiation of regional land use. Scholars often use decoupling models to look into the relationship among resource usage and economic expansion; this study innovatively explores the decoupling link between LUMF on the basis of spatial differentiation [40]. Therefore, this paper reveals the horizontal and vertical comparisons of regional LUMF, makes a judgment on the development trends of different functions, points out the development priorities of each part of the study area, and makes suggestions for national policies.

2.2. The Multi-Dimension Evaluation

On the one hand, the method of extreme difference standardisation is used to process each index for the evaluation of land functions in a dimensionless manner. Secondly, based on multiplicative synthesis, the multi-expert decision making hierarchical analysis method, independence weight coefficient method, and entropy value method are adopted for combined weight calculation, and the combination of subjective assignment methods and objective assignment methods can obtain a better evaluation effect. The independence weight coefficient method and the entropy value method represent two ideas of the objective assignment method, respectively. The former determines the indicator weights based on each indicator's intricate correlation coefficients with other indicators [41], and the larger the complex correlation coefficient, the smaller the independence of the indicator and the smaller the weight value. The latter determines the index weight based on the information entropy of the index; the greater the information entropy, the greater the information of the index, the greater the influence on the comprehensive evaluation, and the greater the weight. Finally, each function is evaluated by using (1).

$$f_j = \sum_{j=1}^{n} W_{ij} P_{ij} \quad (1)$$

The specific steps of the entropy weighting method (EWM) to determine the index weights are as follows.

(1) Standardization of data

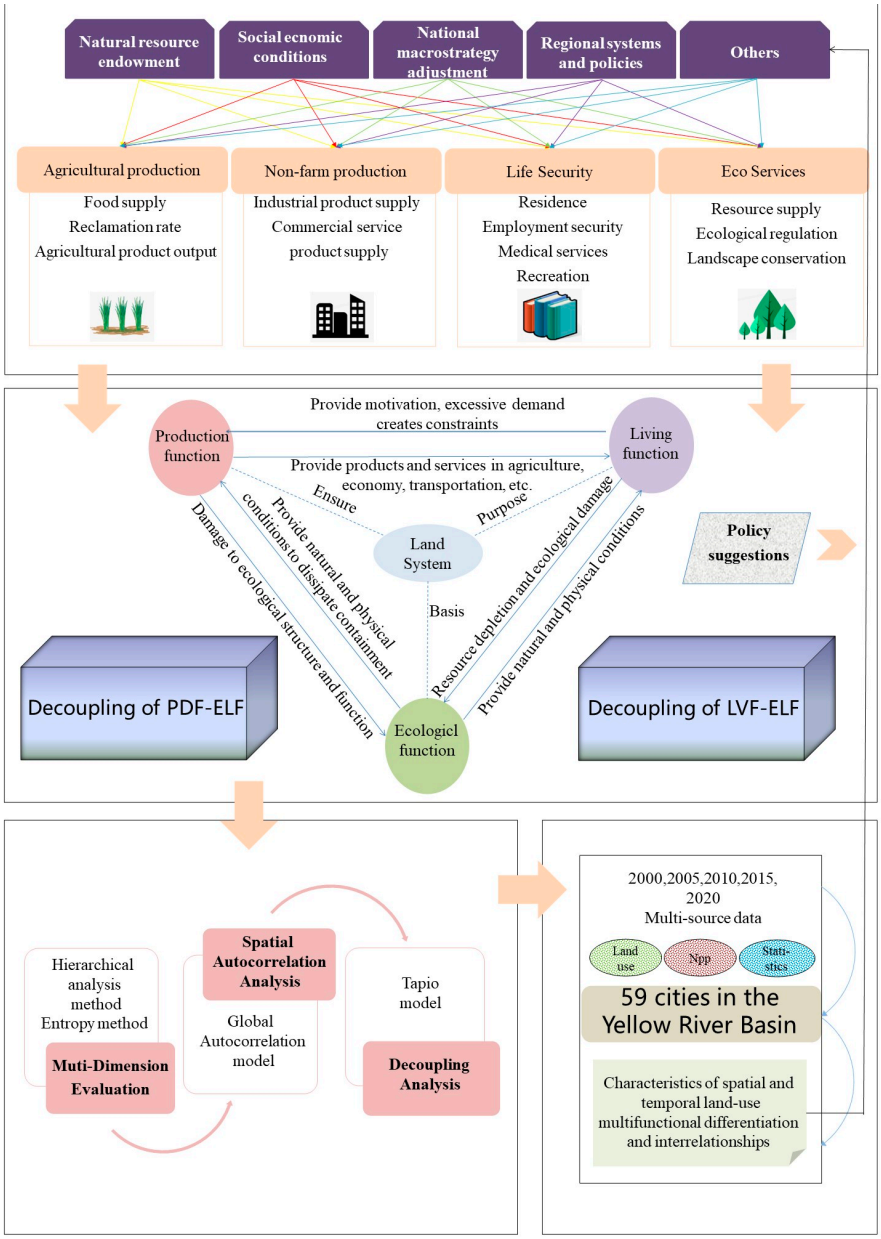


Figure 1. Research framework.

The 25 indicators were normalized using the extreme value method and calculated as follows to eliminate the effect of scale [41]:

$$X_{ij} = \frac{X_{ij} - MinX_{ij}}{MaxX_{ij} - MinX_{ij}} \tag{2}$$

where X_{ij} is the indicator's starting value, $i = 1 \ldots m$, $j = 1 \ldots n$; the numbers m and n represent the number of research units and indicators; the standardized value of x_{ij} is X_{ij}; and Max X_{ij} and Min X_{ij} are the maximum value and minimum value of the j indicator of city i, respectively. In this article, all indicators are positive.

(2) Z_{ij} composite standardized value calculation

$$Z_{ij} = \frac{X_{ij}}{\sum_{j=1}^{n} X_{ij}} \tag{3}$$

(3) Entropy number calculation for the jth indicator

$$H_j = -(\ln m)^{-1} \sum_{i=1}^{m} Z_{ij} \ln Z_{ij} \quad (4)$$

The jth index's information entropy value is H_j. Although a logarithm is not used for the original data in this study, if $Z_{ij} = 0$, a minimal value (0.00000001) is given to Z_{ij} in order to make lnZ_{ij} relevant.

(4) Calculation of the indicator *j*'s weight

$$W_j = (1 - H_j) / \left(k - \sum_{j=1}^{k} H_j\right) \quad (5)$$

The number of indices used to evaluate a single function is k, and W_j is the weight value of the jth indices. Table 1 displays the weight values.

Table 1. PDF/LVF-ELF Decoupling Index Comparison Table.

Decoupling Categories	%ΔELF	%ΔPDF/LVF	DI
Strong decoupling	<0	>0	DI < 0
Weak decoupling	>0	>0	0 ≤ DI < 0.8
Recessive decoupling	<0	<0	DI > 1.2
Growth connection	>0	>0	0.8 ≤ DI ≤ 1.2
Declining connection	<0	<0	0.8 ≤ DI ≤ 1.2
Expansive negative decoupling	>0	>0	DI > 1.2
Weak negative decoupling	<0	<0	0 ≤ DI < 0.8
Strong negative decoupling	>0	<0	DI < 0

2.3. Spatial Autocorrelation Analysis

The exploratory spatial data analysis methods used in this paper include the global Moran index and the cold and hot spot analysis methods [42]. The global Moran index can visually reflect the type of multifunctional spatial correlation of land use in the study area and its spatial distribution characteristics, and better determine whether its distribution belongs to the cluster type, discrete type, or random type.

$$Global\ Moran'I = \frac{\sum_i^n \sum_{j \neq i}^n W_{ij}(X_i - X)(X_j - X)}{S^2 \sum_i^n \sum_{J \neq i}^n W_{ij}} \quad (6)$$

In Equation (6), n is the number of study units, indicating the mean value of study unit attributes; X_i and X_j are the feature values of research modules i and j, respectively; S^2 is the range of score values; W_{ij}, the element of the matrix of geographical weights, is the link relationship between the ith and jth points of spatial objects, which usually have contiguity weight and distance weight, and this paper will be based on the criterion of contiguity weight.

Based on this, this study uses Getis-Ord Gi* on the ArcGIS platform to analyze the spatial clustering of each secondary indicator that affects LUMF by performing a cold and hotspot analysis to better understand where the spatial clustering of high or low value items lies.. Hot spots are areas in the study area with high values of land use functions and vice versa. The specific formula for Getis-Ord Gi* is given below [43].

$$G_i^* = \frac{\sum_{j=1}^n W_{ij} X_j - \overline{X} \sum_{j=1}^n W_{ij}}{S \sqrt{\frac{\left[n \sum_{j=1}^n w_{ij}^2 - \left(\sum_{j=1}^n w_{ij}\right)^2\right]}{n-1}}} \quad (7)$$

where n is equivalent to the total amount of characteristics, X_j is a value for an attribute for feature j, and W_{ij} is the distance and weighting between item i and j:

$$\overline{X} = \frac{\sum_{j=1}^{n} X_j}{n} \tag{8}$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_j}{n} - \left(\overline{X}\right)^2} \tag{9}$$

The Gi* statistics returned for each feature in the dataset is a z-score [40]. The resulting z-scores show where characteristics with high or low values geographically cluster. The clustering of high values is more pronounced for statistically significant positive z-scores with bigger z-scores (hot spots). For statistically significant negative z-scores, the smaller the z-score is, the more intense the clustering of low values (cold spots).

2.4. Tapio Decoupling Model

In the fields of agriculture, energy, building expansion, transportation, and carbon emissions, the decoupling analysis method has been widely applied; relatively few research projects have used the decoupling method to assess the link between various land use functions. Additionally, this work uses a decoupling analysis to examine the connections between the three. In this research, the link between the three functions is investigated using the decoupling analysis method [44]. Currently, there are various methods used to study the decoupling state, such as the integrated analysis of change method and the IPAT model method [45]. Among them, the Tapio elasticity analysis method is widely used in the fields of economic growth and resource environments. In this paper, we use the Tapio elasticity analysis method to measure the elasticity coefficients between production ecology and living ecology in the study area from the perspective of the elasticity concept. The decoupling conceptual foundation is separated into eight logical options based on the extension and elaboration of decoupling theory by Tapio [46] and OECD [47]. They include strong decoupling, strong negative decoupling, weak decoupling, expansion connection, expansion-negative decoupling, decline decoupling, decline connection, and weak negative decoupling types. The significance of each specific type is given in reference and is calculated as follows:

$$DI_{t2-t1} = \frac{\%\Delta ELF}{\%\Delta PDF} = \frac{(ELF_{t2} - ELF_{t1})/ELF_{t1}}{(PDF_{t2} - PDF_{t1})PDF_{t1}} \tag{10}$$

$$DI_{t2-t1} = \frac{\%\Delta ELF}{\%\Delta LVF} = \frac{(ELF_{t2} - ELF_{t1})/ELF_{t1}}{(LVF_{t2} - LVF_{t1})LVF_{t1}} \tag{11}$$

where DI_{t2-t1} is an indicator of the decoupling between years $t1$ and $t2$; ELF_{t1} and ELF_{t2} represent the ecosystem service intensity index in year $t1$ and $t2$, respectively; PDF_{t1}, PDF_{t2}, and LVF_{t1}, LVF_{t2} represent the change rates of PDF and life function in year $t1$ and $t2$, respectively.

3. Research Area and Data

3.1. Research Area

In this study, 59 cities in eight provinces along the YRB (32°35′~43°22′ N, 100°52′~119°19′ N) (Figures 2 and 3) are studied, encompassing 952,600 sq. kilometers, or 9.89% of China's total land area; 213 million people are living there as of 2020. The research area consists of five main urban agglomerations that have a strong agricultural and pastoral sector foundation, accounting for one-third of China's output value; these agglomerations have very rich energy resource reserves, and are also the source of several regional and historical cultures [47,48]. The area is the primary conduit for regional economic growth poles and the layout of population and productivity in the YRB [49].

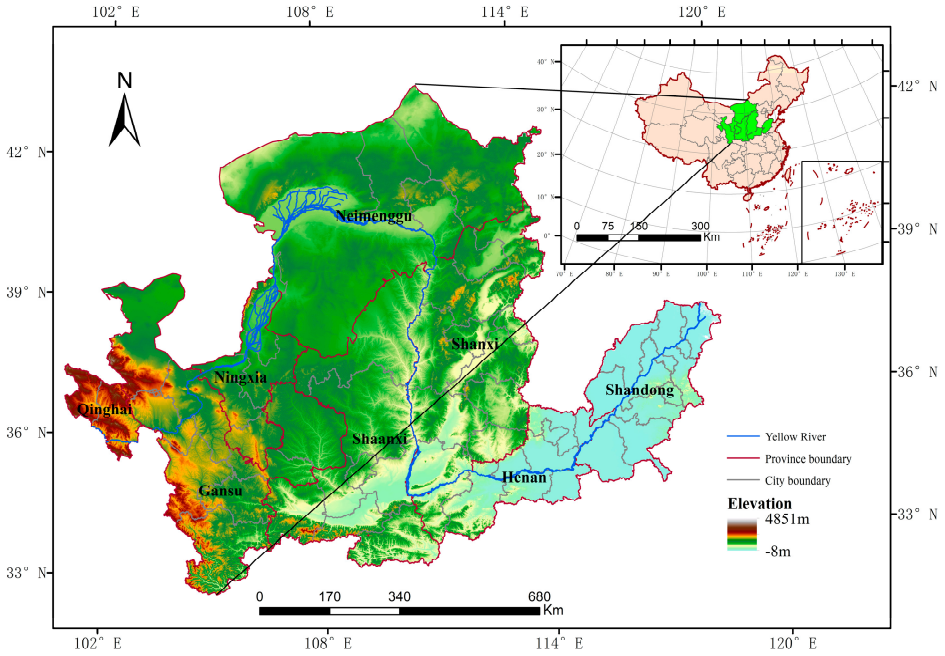


Figure 2. Study area.

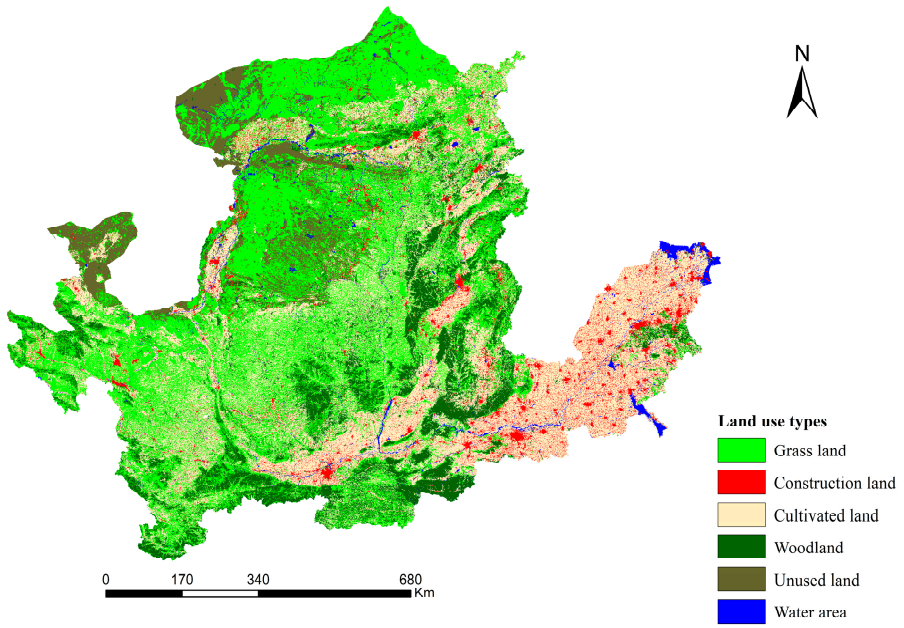


Figure 3. Land use in the study area in 2020.

3.2. Data Sources

Five research years, ranging from 2000 to 2020, were chosen for this investigation. The data types and sources used in this paper are as follows: (1) land use data and data on the administrative boundaries of Chinese municipalities in 2015 are from CAS (http://www.resdc.cn/) (accessed on 4 January 2023). Land use data are for the years 2000, 2005, 2010, 2015, and 2020, with a spatial resolution of 30 m; (2) NPP data from the National Oceanic and Atmospheric Administration (https://www.noaa.gov/) (accessed on 4 January 2020), with a spatial resolution of 1 km; (3) socio-economic data from statistical yearbooks published by provinces and municipalities and statistics on the nation's economic and social progress; and (4) nature reserve boundary data from the China Nature Reserve Specimen Resource Sharing Platform (http://cnpapc.zrbhq.cn/) (accessed on 10 January 2020).

3.3. Building of Indicator System

Based on the principles of comprehensiveness, representativeness, scientificity, and accessibility, the multifunctional land evaluation index system of the YRB was constructed with reference to the existing research results (Table 2), taking into account the land use characteristics of the study area [50–54].

Table 2. Evaluation index system of LUFs. (+ indicates that the indicator has a positive effect on the system).

Target Layer	Factor Layers and Weights	Indicator Layer	Description	Properties	Index Weight
PDFs (0.40)	Agricultural production function (0.437)	Average land grain production	Total grain output/cultivated land area (kg·ha)	+	0.0797
		Food production per capita	Total grain output/total population (kg)	+	0.1892
		Reclamation rate	Cultivated land area/total land area (%)	+	0.1637
		Meat production per capita	Meat output per capita (kg)	+	0.2261
		Total output value of agriculture, forestry, animal husbandry, and fishery	Total output value of agriculture-forestry-stockbreeding-fishery (million)	+	0.3413
	Economic development function (0.563)	Economic Density	Regional GDP/total area (billion yuan·km^{-2})	+	0.6742
		The proportion of secondary and tertiary industries	Output value of secondary and tertiary industries/GDP (%)	+	0.0324
		GDP per capita	Regional GDP/total population (million)	+	0.2934
LVFs (0.40)	Traffic carrying function (0.129)	Road network density	Road mileage/total area of the region	+	1.0000
	Residential home function (0.346)	Population density	Total population/total area of the region (person·km^{-2})	+	0.4897
		Construction land ratio	Construction land area/total land area (%)	+	0.5103
	Employment support function (0.282)	Population density in the workforce	Total employed population/total area of the region (person·km^{-2})	+	0.9074
		Tertiary sector as a percentage of employed population	Tertiary sector employed population/total employed population (%)	+	0.0926
	Social security function (0.151)	Urban-rural income balance index	Rural per capita income/Urban per capita income (%)	+	0.5344
		Per capita income of rural residents	Per capita income of rural residents (yuan)	+	0.4578
		Number of beds in health facilities for 10,000 people	(Number of beds in health facilities/total population)/(beds/million people)	+	0.0078
	Cultural and leisure function (0.092)	Tourist arrivals	Regional annual tourist arrivals (million people)	+	0.5874
		Greening coverage of built-up areas	Urban built-up area covered by greenery/built-up area (%)	+	0.0446
		Number of books per capita in public libraries	Number of books in public libraries/total population (volume)	+	0.3680

Table 2. *Cont.*

Target Layer	Factor Layers and Weights	Indicator Layer	Description	Properties	Index Weight
ELFs (0.30)	Resource supply function (0.251)	Water resources per capita	Total water resources/total population (m^3)	+	1.0000
	Ecological regulation function (0.423)	Value of Ecosystem Services	Referring to the improved method of Xie et al. [4], paddy field, dry land, garden land, wooded land, shrubland, grassland, and water were counted at 3.89, 4.01, 26.96, 22.95, 15.22, 19.69, and 125.61 each (Yuan·ha)	+	0.2585
		npp	The average content of carbon in atmospheric CO_2 fixed by vegetation on a regional scale	+	0.2892
		Percentage of ecological space	(Water area + forest area + garden area + grassland area)/village land area (%)	+	0.4523
	Landscape conservation function (0.326)	Nature reserve area share	Nature reserve area/land area (%)	+	0.7334
		Forest cover	Woodland area/land area (%)	+	0.2666

4. Results

4.1. Changes in Land Use Functions through Time and Space

Firstly, the study area was divided into three spatial levels: upper, center, and lower, and the total value of LUFs was calculated. From 2000 to 2020, the total value of the PDF–LVF-ELF showed a lower Yellow River > middle Yellow River > upper Yellow River (Figure 4). Among them, the overall total value of LUFs in the upper and center cities of the Yellow River does not change much over time, and the total value of LUFs in the Yellow River's lower cities decreases over time.

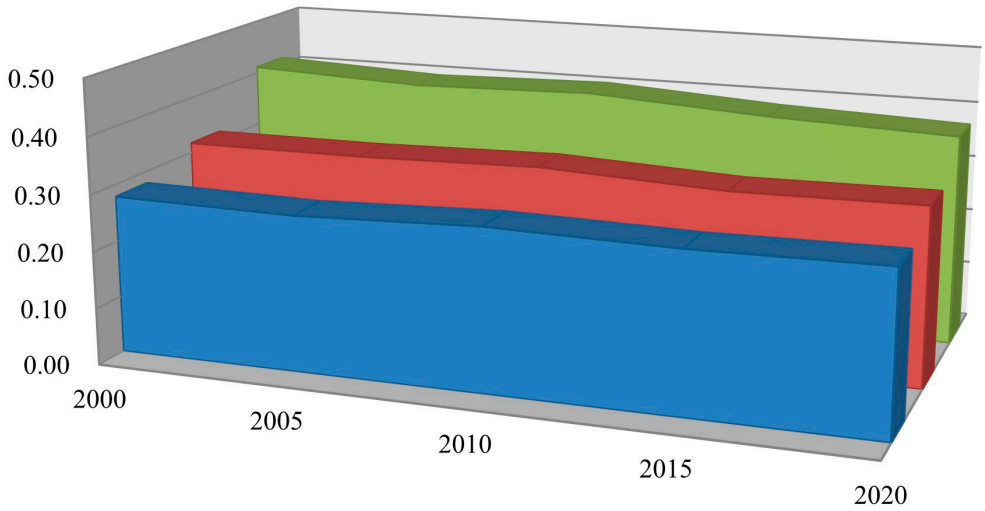


Figure 4. Changes in LUFs in various parts of the YRB. (Green for downstream, red for midstream, blue for upstream).

According to the comprehensive evaluation results, the temporal and geographical variations in the evaluation results for functions of production, living, and ecology in the study area were mapped using GIS technology (Figure 5), and it was found that the spatial distribution of the change values for the PDF, LVF, and ELF showed non-equilibrium type characteristics. Regarding the change in the PDF, it shows obvious spatial aggregation characteristics during 2000–2020, with numerous cities within the Yellow River's upstream and middle reaches increasing their PDF, among which Yulin in Shaanxi Province and

Guyuan in Ningxia Hui Autonomous Region have the highest growth rates of 0.78 and 0.74, respectively, while a series of cities in the downstream of the Yellow River, Henan Province, and Shandong Province show a decreasing trend in the value of PDF from 2000 to 2020. The value of the LVF in the study area during 2000–2020 is unbalanced, among which Erdos, Zhongwei, Guyuan, and Baiyin have the fastest growth rates, while Xining, Qingyang, Xinzhou, and Datong in the upper and middle reaches of the Yellow River have a decreasing trend. In the period 2000–2020, the overall ELF of the study area changed slowly, among which Liaocheng City, Dezhou City, and Weinan City in the Yellow River's lower and central sections increased more, while Dingxi City and Ordos City decreased slightly.

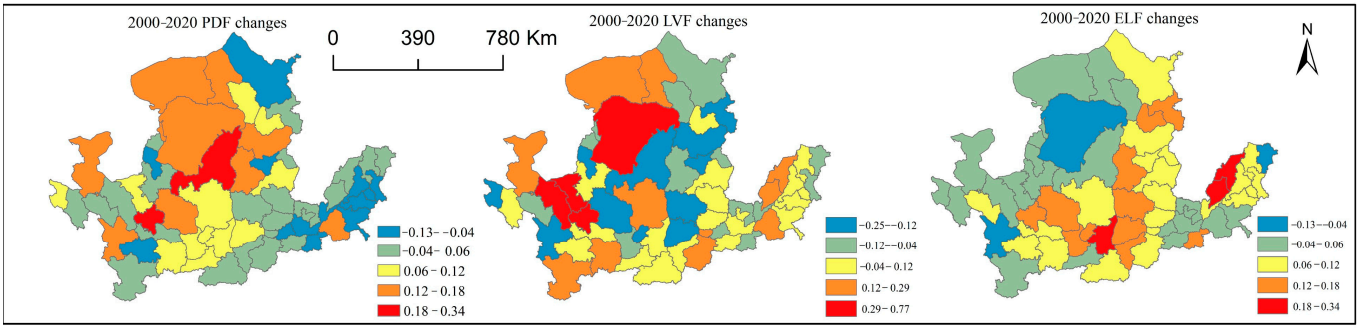


Figure 5. Spatial and temporal rates of change of LUFs.

4.2. Spatial Aggregation Analysis of LUFs

Spatial Aggregation Analysis of Land Use Functions

The distribution of the land's productivity, habitation, and ecological functions was calculated using the global Moran's indicator and a cold/hot spot analysis (Figure 6). The calculation results of the global Moran's I index confirm that the three have obvious positive spatial correlation [50], i.e., a strong interaction of adjacent units and agglomerative spatial phenomena. Specifically analyzing the spatial cold and hot spots of each secondary index, the hot spots of the agricultural production function are located in most cities in Shandong Province, and the cold spots are located in Taiyuan City and the surrounding cities; there are two hot spots of the economic development function, namely, the city cluster around Jinan City in Shandong Province and the city cluster around Zhengzhou City in Henan Province, and the cold spots are the areas centered on Baiyin City, Guyuan City, and Pingliang City in the west; the traffic carrying the hot spots of ecological regulation function are located in Tianshui City, Longnan City, and the nearby cities, as well as four cities in the heart of the province of Shanxi, and the cold spots are located in most cities in the Yellow River's lower reaches in the southeastern part of the study area; the research area's south contains the hotspots for landscape conservation function, and the cold spots are five cities on the border between the provinces of Henan and Shandong.

4.3. Production Ecology and Living Ecology Decoupling Analysis

In order to fully reveal the relationship between the ELF, PDF, and LVF, the scatter plots between the ELF, PDF, and LVF were first analyzed (Figure 7). From the scatter plots, it can be seen that there is a negative linear relationship between the ELF, PDF, and LVF, but the slope of the linear relationship between the two is small when the values of the PDF and LVF are low, and the slope gradually increases as the values rise. This shows that when the land use PDF and LVF are low, there is a negative but not obvious effect on the ELF, and as the land use PDF and LVF rise to a certain threshold, their negative effect on the ELF is reflected more obviously.

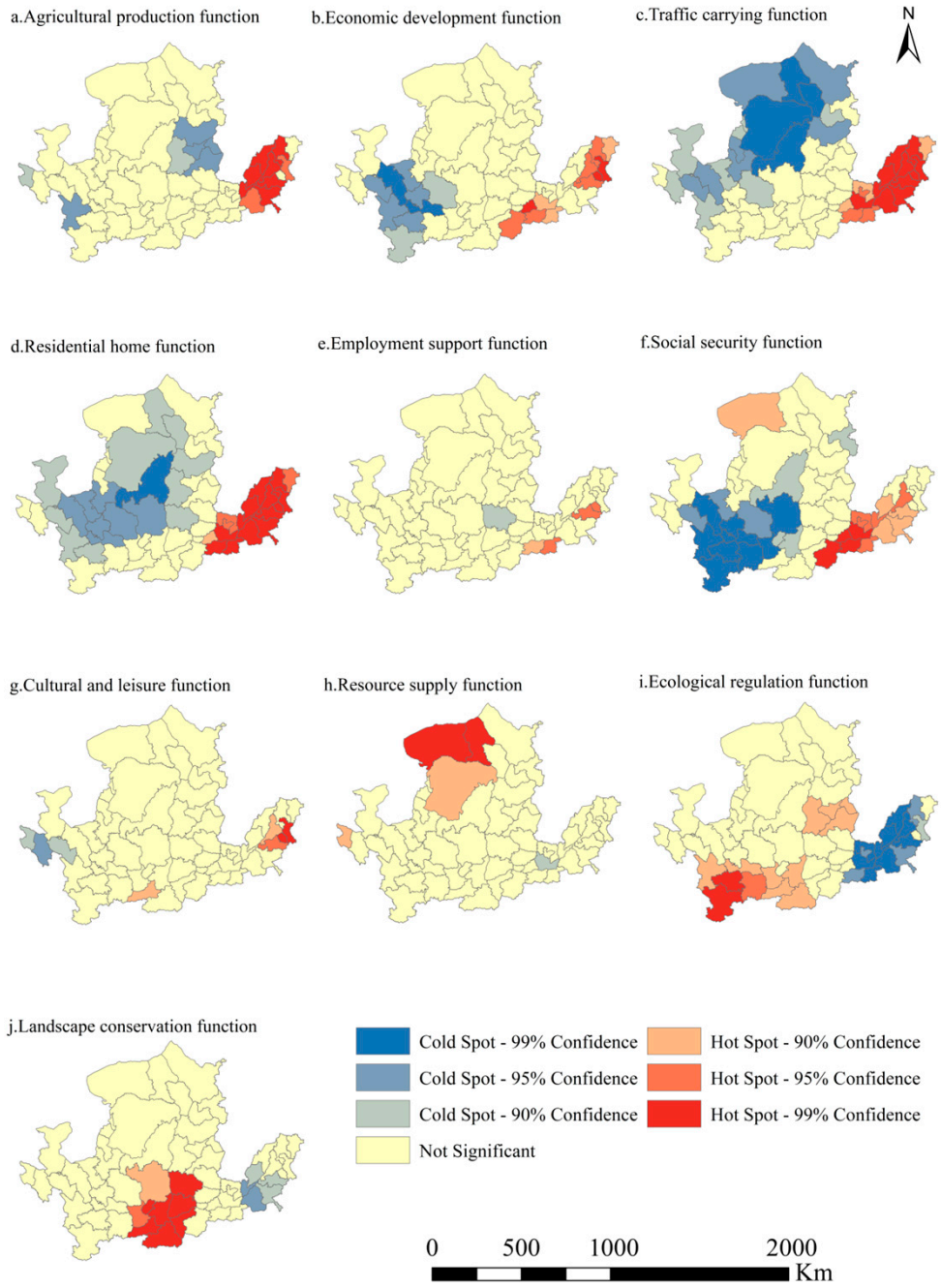
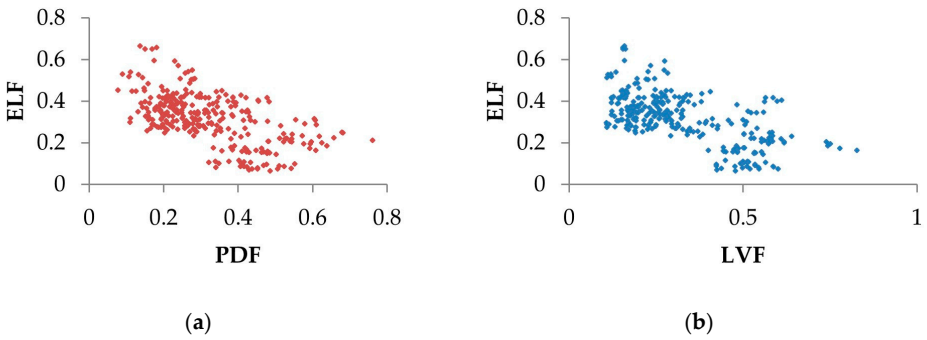


Figure 6. Spatial aggregation of secondary functions.



(**a**) (**b**)

Figure 7. Scatterplot of land use functions in the YRB from 2000 to 2020 (**a**) PDF-ELF scatter plot; (**b**) LVF-ELF scatter plot.

In order to further explain the relationship between the ELF, PDF and LVF of land use in different regions of the area of investigation, the decoupling relationship between the ELF, PDF, and LVF from 2000 to 2020 was analyzed (Figure 8), and the statistical results of its spatial distribution characteristics and the proportion of different logical types of municipalities were obtained (Table 3). Overall, the PDF-ELF and LVF-ELF, which are in strong decoupling and strong negative decoupling relationships, are higher, reaching more than 50% in all years. The strong decoupling type represents the enhancement of the PDF and LVF leading to the reduction in the ELF, and this development model is in a dilemma, while the strong negative decoupling type represents the reduction in the PDF and LVF, leading to the improvement in the ELF, and this type is a sustainable development type. After 2015, the proportion of this type of expansion-negative decoupling increases more, and expansion-negative decoupling represents that the increase in the PDF or LVF leads to the increase in the ELF, and the increase in the ELF is higher than the increase in the PDF or LVF, which is the most desirable development model.

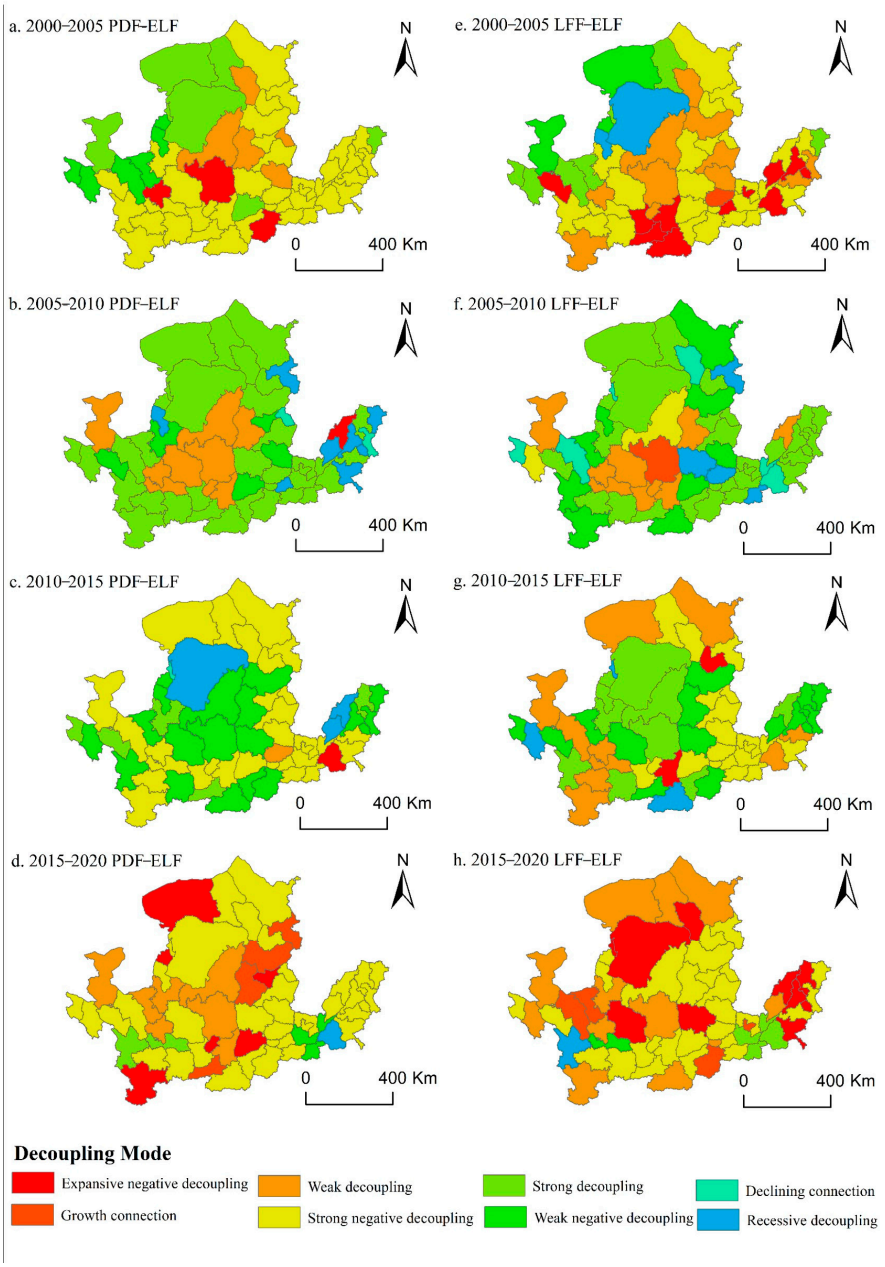


Figure 8. Decoupling of LUFs.

Table 3. Logical possibilities statistics.

Decoupling Categories	2000–2005 (PDF-ELF)	2005–2010 (PDF-ELF)	2010–2015 (PDF-ELF)	2015–2020 (PDF-ELF)	2000–2005 (LVF-ELF)	2005–2010 (LVF-ELF)	2010–2015 (LVF-ELF)	2015–2020 (LVF-ELF)
Expansive negative decoupling	5.08	1.69	1.69	10.17	16.95	0.00	3.39	15.25
Growth connection	0.00	0.00	0.00	6.78	1.69	1.69	0.00	6.78
Weak decoupling	8.47	15.25	1.69	11.86	18.64	15.25	16.95	20.34
Strong negative decoupling	64.41	0.00	50.85	61.02	42.37	3.39	33.90	47.46
Strong decoupling	11.86	59.32	8.47	3.39	11.86	47.46	16.95	6.78
Weak negative decoupling	10.17	8.47	30.51	5.08	5.08	15.25	23.73	1.69
Declining connection	0.00	3.39	1.69	0.00	0.00	10.17	0.00	0.00
Recessive decoupling	0.00	11.86	5.08	1.69	3.39	6.78	5.08	1.69

At the same time, some cities have this type of decoupling. Decline decoupling is also an important type of decoupling logic, and the decrease in the PDF or LVF in this type of municipal unit leads to the decrease in the ELF, and the decrease in the ELF is greater than the decrease in the PDF or LVF, so this type of decoupling is unsustainable.

5. Discussion

5.1. Land Use Function and Its Decoupling Relationship

The uncoordinated development of land use change will bring challenges to build a balanced pattern of agriculture, city, and ecology [55]. In this study, 10 sub-functions and 25 indicator systems were established based on the production function (PDF), living function (LVF), and ecological function (ELF) of 59 cities in the Yellow River Basin. The spatial and temporal changes in various functions of land use in the study area from 2000 to 2020 were analyzed by using the subjective–objective combination of the empowerment method and exploratory spatial data analysis method. The theoretical basis of decoupling analysis was utilized to detect the decoupling relationship among the three functions.

According to the findings of the comprehensive assessment, in the study region, the total value of LUFs in general shows downstream > midstream > upstream. Meanwhile, our study concludes that the land use level of the ELF in the YRB cities has improved as a whole from 2000 to 2020; many towns downstream of the YRB have different degrees of decline in land PDF; Xining, Qingyang, Xinzhou, Datong, and other cities upstream of the YRB have an obvious decline in LVF. These indications are consistent with the research of other scholars [56].

This study explored the decoupling relationship between land use functions, and in general, the PDF-ELF and LVF-ELF were in the state of strong decoupling and strong negative decoupling relationships, respectively, and the proportion was high, both exceeding 50% of the cities, which indicated that the process of industrial and agricultural production and ecological protection in the whole Yellow River Basin were still in a dilemma, which was due to the fact that industrial relocation and urban expansion have led to the loss and fragmentation of agricultural land and natural landscapes, making it difficult to maintain ecological functions [57]. However, the development process of the land to give residents living functions and the health of the ecosystem are in a sustainable and benign state, and the provision of ecological services and comprehensive remediation projects on agricultural and forest lands have led to a certain degree of ecosystem preservation [58]. The expansion-negative decoupling state appeared considerably more frequently in both groups of subjects after 2015, indicating that an increase in the PDF or the LVF led to an increase in the ELF and the increase in the ELF is higher than the increase in the PDF or LVF, which is the most favorable development pattern for high-quality and sustainable development. In recent years, in the Yellow River Basin as a whole, in the active promotion of vegetation restoration projects and returning farmland to forest and grassland projects, soil erosion has been weakened and the vegetation cover in the watershed has increased, and at the same time, through comprehensive management and ecological restoration and management, the economic benefits have been maximally retained [59].

5.2. Spatial Guidance of Land Use Functions and Policy Recommendations

The study claims that the YRB 's ecological conservation and management approach has contributed in some way in recent years, through the setting up of major ecological protection and restoration projects, which has led to an overall steady rise in the ELF during the study period, with only three cities showing a significant decline. The Yellow River's central reaches have obvious advantages in landscape conservation and resource supply functions, but the overall level of ecological regulation function is not high and should be improved through soil and water conservation and desertification control. PDF development in the study area is uneven, with higher levels of agricultural production in Shandong Province than in other regions, while non-agricultural economic development revolves around two urban clusters around the cities of Zhengzhou and Jinan, with an overall rise in other parts. However, PDF is still inadequate for developing the following high quality [60]. The inadequate development of people's livelihood is a major weakness in the development of the YRB, with more gaps in public services and infrastructure in all provinces and regions. Medical and health facilities are insufficient, the disparity between urban and rural populations' earnings is lower than the national average, and the LVF level of most cities has increased during the study period; upstream of the YRB, the LVF level has improved more significantly, which is a positive trend. In 2021, the Communist Party of China Central Committee and the State Council published *the Yellow River Basin Outline of the Plan for Ecological Protection and High-Quality Development*, and in 2022, four departments, including the Ministry of Ecology and Environment and the Ministry of Natural Resources, jointly issued *the Plan for Ecological and Environmental Protection of the Yellow River Basin*. The above plans and national strategies are more conducive to the coordinated development of LUFs to boost the overall level of LUFs on the basis of further enhancing ecological protection along the Yellow River, to increase the effectiveness of land use, to compensate for the weaknesses of LUFs, and to raise the overall level of LUFs [61].

According to the spatial distribution results of the LUF, the upper reaches of the YRB have a superior ecological environment and should take eco-tourism, high-value agriculture, etc., as the main development direction, rationally develop mountain and water resources, and build a tourism development model combining ecology, culture, and industry; the middle reaches of the YRB should deepen the optimization of the spatial layout to form an interdependent and synergistic urban belt to connect the exchanges between the upper and lower reaches; and the downstream areas of the YRB should strengthen the development of the coastal economy, build an efficient industrial chain of ports, logistics, and industrial support, and promote the transformation of old and new kinetic energy. At the same time, the downstream area should also pay attention to the protection of the ecological environment and strengthen the construction of sponge cities.

5.3. Limitations and Future Research Directions

In this research, more indicators have been selected for the evaluation of LUFs at a large scale and the special geographical conditions of the YRB, but these indicators still cannot cover all LUFs, and more indicators still need to be explored in the future due to the availability of data [62].

In the future, we will use spatial data such as high-resolution images, POI data, and more quantitative models to improve the accuracy of the evaluation results of land use functions and try to explore the interaction between functions from multiple dimensions and scales in order to deepen the study of land use functions and provide a basis for decision making in land spatial planning and management.

6. Conclusions

The multifunctionality of land has been widely recognized. However, the spatial and temporal evolution of LUFs and their decoupling from each other is often overlooked by urban planners and policy makers.

This study carefully examines the geographical and temporal differentiation properties of various land use functions in each section of the YRB, using the YRB as a bigger research scope. Based on the outline of the plan for ecological protection and high-quality development in the YRB, as well as the geographical environment and development degree of the YRB, the evaluation models and indicators of land use functions in each city were constructed from the three dimensions of production, living, and ecology, which can better reflect the complex interaction between multiple functions of land use. Further, the decoupling relationship between different functions of land use has been studied in depth. Compared with previous studies, this study not only considered a single function but also integrated different functions of multiple indicators. In terms of scale, the municipal administrative unit and a larger span of the study area were chosen so that this study can be used as an example of a multifunctional study of land use on a large scale.

In terms of research results, the LUFs values of cities upstream of the YRB and midstream of the YRB have changed less, and the LUFs values of cities downstream of the YRB have decreased, while the ELFs in the study area have significantly increased after 2010, and the decoupling relationship between the ELF, PDF, and LVF has increasingly developed to the good side, thanks to the systematic management and policy guidance of ecological problems in the YRB.

The empirical results of the YRB case considered in this study provide relevant insights into how the LUF decoupling analysis can contribute to supporting spatial planning and land use management, thereby better establishing the coordinated development of urban–rural areas, especially in developing countries such as China, where land availability is limited.

The development status and degree of coupling and coordination of the "three living spaces" in the upper, middle, and lower reaches of the YRB are different, and the government should formulate a clear low-carbon development plan based on the current development status, resource endowment, and industrial demand of the localities, actively guide the transformation and upgrading of the industrial structure of the cities, and strengthen the inputs in the fields of energy, transportation, and pollution control.

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