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Spatiotemporal Differentiation and Coupling Coordination Relationship of the Production–Living–Ecological Function at County Scale: A Case Study of Jiangsu Province

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Abstract: Land is multifunctional and includes production, living, and ecological functions (PLEF). Each aspect of PLEF is critical to the stability of human and natural ecosystems, and the balanced coordination of the three is an important guarantee of sustainable development. The study of the coupling and coordinated relationship of the three functions is of great significance to comprehensively optimizing the allocation of territorial space and promoting the coordinated and sustainable development of the national territory. Taking Jiangsu as a case study, based on the perspective of PLEF, this research constructed a PLEF evaluation index system adapted to rapidly urbanizing areas at the county scale and adopted the modified coupling coordination degree model (CCDM) for in-depth analyses of their coupling and coordinated relationships. The results of this study showed that the spatial distribution of PLEF had obvious heterogeneity, with living function (L) and ecological function (E) presenting as high in the south and low in the north, and production function (P) presenting as high in the middle and low in the north and south of Jiangsu; from 2010 to 2020, the production function steadily increased, the living function showed obvious signs of improvement, while the ecological function remained basically stable. The coupling degree and coupling coordination degree formed a spatial pattern with the intersection belt of North and Central Jiangsu and Central and South Jiangsu as the high-value area; from 2010 to 2020, both the coupling degree and the coupling coordination degree showed an upward trend. In the future, differentiated development strategies should be implemented according to the law of coupling and coordinated evolution and different regional characteristics. This study will provide a more appropriate reference for promoting the coordinated development of PLEF in rapidly urbanizing areas and formulating county policy planning.

Keywords: land use multifunctionality; production–living–ecological function; coupling coordination degree model; spatial–temporal pattern; Jiangsu province

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1. Introduction

The human–earth relationship refers to the interactions and linkages between human beings and the geographic environment. The concept first appeared in geographic studies in the 20th century [1]. In recent years, as global environmental change and the sustainable development agenda have attracted increasing attention, the study of human–earth relations and human–earth coupling has become a key area of concern for international academics and policymakers [2]. This relationship essentially explores the intricate ways in which human beings interact with the land [3]. This interaction is not unidirectional but constitutes an interdependent system [4]. In addition, the complexity of this interaction is reflected not only in resource utilization and transformation of the environment [5] but also in its shaping of human social structures and development patterns [6].

Land is the material basis and fountain of resources for humanity's social and economic development and the space and environment in which various living things survive, thus making it a comprehensive system composed of economic, social, and ecological subsystems [7]. According to the main function, land could be classified as production land, living land, and ecological land (production–living–ecological land (PLEL)) [8], which dominate production function, living function, and ecological function (production–living–ecological function (PLEF)), respectively [9]. Each aspect of PLEF is critical to the stability of the human–natural ecosystem, and the balance of the three is a significant guarantee of sustainable development [10–12]. It should be noted that the three aspects of PLEL are closely interconnected and mutual; transformation among them could be induced easily via anthropogenic activities [13]. Over the past decades, rapid industrialization and urbanization have swept the globe. To satisfy the increasing construction land demand of urban expansion and population growth, a large quantity of agricultural land and ecological land (such as forest, grassland, and unutilized land, etc.) has been occupied. Consequentially, large quantities of ecological land have been forced to transfer to agricultural land to feed the growing population [14–16]. As a result, the competition and interference among various land use types has become increasingly intense, and the contradictions and conflicts among the PLEL have become increasingly prominent [17–19]. As the biggest developing country, China has undergone unprecedented urbanization in human history since its reform and opening-up in 1978; thus, it has undergone land utilization contradiction and conflicts and consequent ecological degradation and environmental pollution [20,21], all of which exert great impact both domestically and internationally. Recently, the Chinese government has placed the ecological civilization construction in a prominent position, aiming at comprehensively optimizing the allocation of territorial space and promoting coordinated and sustainable development [22], which is challenging but urgent. Therefore, more work on the optimization of the three spatial patterns for sustainable urban development should be undertaken.

Currently, issues related to PLEF have attracted extensive attention from international research scholars. There has been plenty of research on the production–living–ecological theory. In terms of research scales, studies have covered areas from the smaller street scale [23] to the larger provincial [24] and municipal [25] scales, and most studies have focused more on scales such as the rural scale [11,19,26,27] and a particular type of district [28–31] but less on the county/medium scale. Given that the majority of current policies are enforced and managed at the county level, an in-depth study of the county mesoscale will make it easier to formulate regional policies and implement precise management. Therefore, more case studies should be conducted at the county mesoscale to provide relevant empirical evidence. In terms of research content, studies have mostly focused on the conceptual connotation [32], classification system [33], quantitative evaluation [34], spatial identification and optimization [19,29], spatial–temporal pattern evolution [30,35], multi-scenario simulation [36], and influencing factors [13] of the production–living–ecological function, etc. However, few studies on the quantitative evolution of the interaction among the three functions have been systematically carried out. It is necessary to assess the status and performance of the three functions as a whole.

As the study progressed further, the spatial autocorrelation analysis [37,38], mechanical equilibrium model [39], coupling coordination degree model (CCDM) [12,40], Pearson correlation coefficient [41], geographically weighted regression model [42], and other methods were introduced to describe the relationship between PLEF. Coupling, as a physical concept, refers to the phenomenon of two (or more) systems or forms of motion affecting each other through various interactions [43]. In addition, the coupling degree is a description of the extent of this interaction [44], but it cannot clearly show the specific relationship among the systems [11]. In addition, research has found that the improvement of one function will cause a change of another kind [45]. A new index was needed in order to represent this situation, so the CCDM, which can solve this problem, has come into being. The CCDM has found extensive application in geography for the analysis of the coupled and coordinated development of various systems, including socioeconomic [46,47], urbanization [48], tourism [49], environmental [50], carbon emission [51], and land use [52] systems. This is primarily attributed to its capacity to depict the inter-relationship among multiple systems in a simple and straightforward way. Additionally, the model has been widely employed in the study of the production–living–ecological function [11,12]. In recent years, the CCDM was further modified and developed by scholars, which has improved the feasibility and accuracy of the model [53]. Therefore, here, we adopted a modified CCDM to carry out this study in the hope of obtaining some more significant and meaningful results.

In the context of increasing competition for territorial spatial resources and the urgent need for sustainable and high-quality regional development, the coupling and coordinating relationship among the PLEF have received much attention. However, the existing research and comprehension of this relationship at the county level in rapidly urbanizing areas are somewhat insufficient. As one of the most economically developed regions in China, Jiangsu, whose GDP reached 11.6 trillion RMB in 2021, ranking the second in China (and 25 counties in the province were among the top 100 counties in China) [54], has long faced the typical challenges of sustainable development. However, there are large regional variations within it. Meanwhile, because of the similarities in both economic development and urbanization between the internal development structure (southern, central, and northern of Jiangsu) and the overall regional development structure of China (eastern, central, and western), the study of Jiangsu's problems will not only clarify the current state of development in itself but will also provide a certain degree of reference to China and other developing countries. Therefore, this study takes Jiangsu as a case study. First, combining the results of previous research and the current state, we constructed a county-scale indicator system adapted to rapidly urbanizing regions to evaluate the PLEF. Subsequently, utilizing the CCDM, we measured the coupling degree and the coupling coordination degree of the study units in 2010, 2015, and 2020. Through an extensive analysis, we delved into the spatial and temporal evolution of PLEF and investigated the interconnected relationship among the study units, aiming to provide a reference basis for regional sustainable development and the optimization of the national land space.

2. Materials and Methods

2.1. Study Area

Jiangsu is located in the eastern coastal region of China, the lower reaches of the Yangtze River and the Huai River, and is an important part of the Yangtze River Delta region, which is located in the warm temperate zone and subtropical climate junction area, with mild climate, abundant light and heat, abundant water resources, and flat terrain. The plain area accounts for 86.89% of the whole province. Jiangsu is one of the important grain-producing provinces and regions in China. In 2021, the GDP reached 11.6 trillion yuan, ranking second in the country, and 25 counties in the province are ranked among the top 100 counties in China, making it one of the most economically prosperous provinces in China. In recent years, the imbalance of economic development in this region has become increasingly prominent, and the spatial heterogeneity is increasingly obvious. A series of problems, such as urban diseases, declining resource carrying capacity, and decreasing species diversity, arising from urban expansion, reduction of arable land, and environmental damage, are becoming more and more prominent [55]. In the context of territorial spatial planning, how to coordinate the development of PLEF has become an urgent problem to be solved.

We consider the frequent adjustment of administrative divisions in Jiangsu during the study period, such as "town adjusted to city" and "county adjusted to district", which occurred in many regions. In addition, due to the small area of cities and municipal districts in Jiangsu, in order to ensure the availability of data, this study was based on the administrative divisions of Jiangsu in 2020, and the municipal districts were merged into 1 unit, and a total of 53 county-level research units were obtained, as shown in Figure 1.

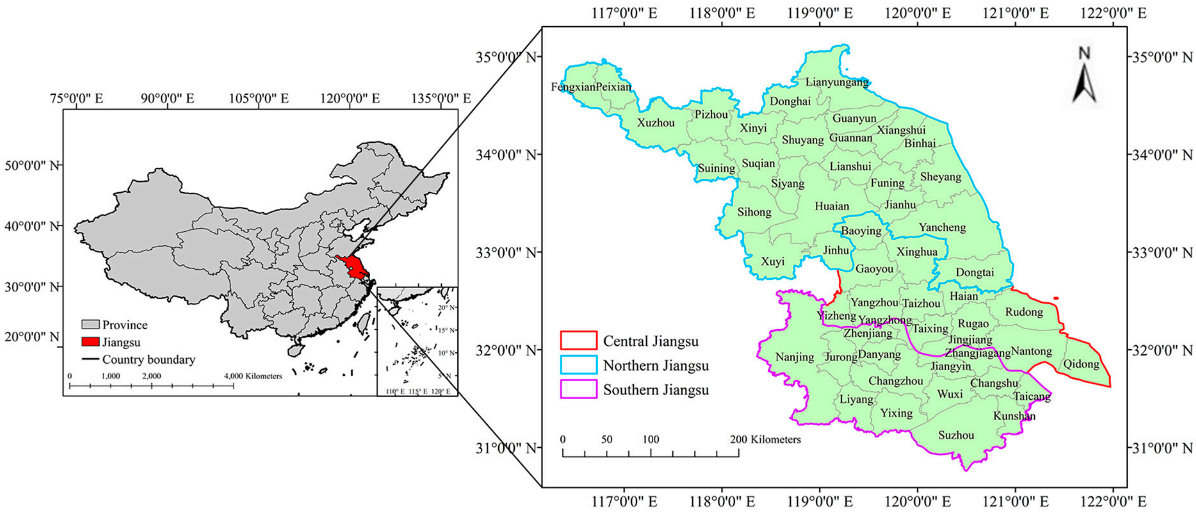

Figure 1. Research area of Jiangsu.

2.2. Data Sources

2.2.1. Data Source and Methodological Process

The research data mainly include land use/land cover remote sensing monitoring data, resource environmental data, and the socioeconomic statistics of 53 units in 2010, 2015, and 2020. Among them, the land use/land cover remote sensing monitoring data are derived from the Resource and Environmental Science and Data Center (http://www.resdc.cn, accessed on 5 March 2023) of the Chinese Academy of Sciences, which are 1 km × 1 km raster data, and the land use types are subdivided into 6 first-level types and 25 s-level types of arable land, forest land, grassland, water area, residential land, and unused land. The resource environmental data and socioeconomic statistics for 2010, 2015, and 2020 are from the 2011, 2016, and 2021 Jiangsu Statistical Yearbooks and Jiangsu Provincial City and County Yearbooks, respectively. The methodological process is shown in Figure 2.

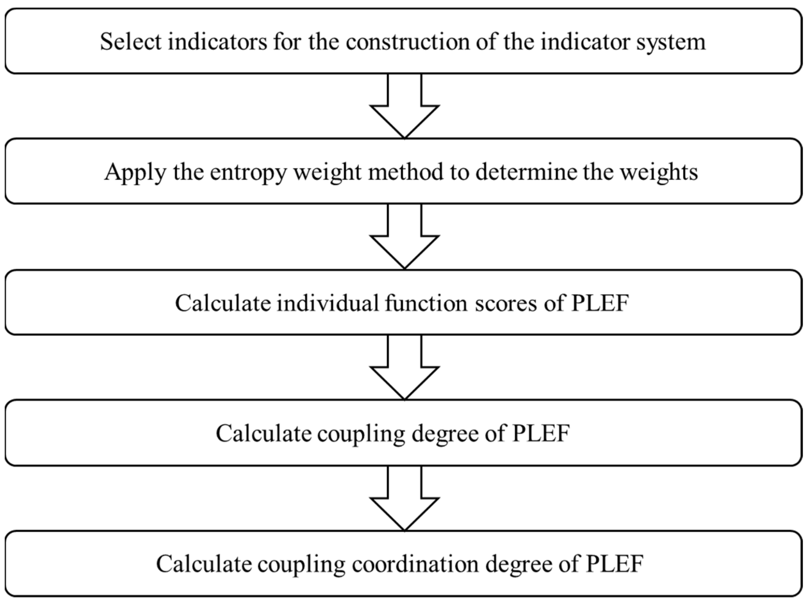

Figure 2. The methodological process.

2.2.2. Index System

Territorial space is a space where multiple functions are intertwined. By further refining and extending its core functions, we could obtain the PLEF, which refers to the ability of the land space to provide various products and services for human beings and to continuously meet the different needs of human beings for survival, working, recreation, and living [8].

The production function is the ability of human beings to receive economic benefits through direct labor on the land or the capability to utilize the land as a spatial vehicle for social production and to receive a variety of material goods and services. According to the corresponding connotation of production function, we selected the grain yields to characterize the level of grain production [56]. The land settlement rate and arable land per capita were chosen to characterize food production potential [11], and the primary sector output per capita and secondary sector output per capita were selected to characterize the production function [57]. The interpretations of the above indicators are shown in Table 1.

Table 1. Selection of indicators for production function.

Criteria	Basic Level Indicator	Index Interpretation	Direction	Unit
Production function Index	Per unit area yield of grain	Total grain output/cultivated land area	+	Ton/ha
	Per capita arable land	Total area of cultivated land/total population	+	m^2/person
	Land reclamation rate	Total area of cultivated land/total area	+	%
	Per capita output value of primary industry	Gross output value of the primary industry/total population	+	10^4 yuan/person

Living function refers to the ability of national space to provide infrastructure and spatial carriers for social activities, including human habitation, recreation, consumption, and travel, embodying the essence of the quality of human existence [42]. According to the corresponding connotation of living function, we selected the density of the road network, the proportion of built-up land, the retail sales of social consumer goods per capita to characterize the capacity of the county to provide services for residents' travelling activities, the carrying capacity of the county to provide various social activities for residents, and the level of services received by residents' consumption activities, respectively [25,28,29]. Moreover, the electricity consumption per capita (excluding industry) and public budget expenditure per capita were chosen to indicate the living standard of the residents in the county. The interpretations of the above indicators are shown in Table 2.

Table 2. Selection of indicators for living function.

Criteria	Basic Level Indicator	Index Interpretation	Direction	Unit
Living function Index	Density of road network	Highway mileage/total area	+	km/km^2
	Per capita retail sales of Consumer goods	Total retail sales of consumer goods/total population	+	10^4 yuan/person
	Proportion of construction land	Total area of construction land/total area	+	%
	Per capita household electricity consumption	(Total annual electricity consumption–total industrial electricity consumption)/total population	+	10^4 kw·h/person
	Per capita public budget expenditure	Total public budget expenditure/total population	+	10^4 yuan/person

Ecological function does not directly provide material goods and places for human activities but is the ability to maintain the basic environmental conditions for human production and living [12]. According to the corresponding connotation of ecological function, we opted for the green cover, ecological service value per unit area, and habitat quality index to characterize the ability of the county to provide ecological environment. In addition, the ecological pressure was characterized by the intensity of agricultural fertilizer inputs [36,58]. The interpretations of the above indicators are shown in Table 3.

Table 3. Selection of indicators for ecological function.

Criteria	Basic Level Indicator	Index Interpretation	Direction	Unit
Ecological function Index	Agricultural fertilizer input intensity	Total application amount of agricultural fertilizer/cultivated land area	-	Ton/ha
	green coverage ratio	Green area/total area	+	%
	Ecological service value per unit area	Total value of ecological services/total area	+	10^8 yuan/ha
	Habitat quality index	Abio × (0.35 × Forest area + 0.21 × Grassland area + 0.28 × wetland area + 0.11 × agricultural acreage + 0.04 × Construction land area + 0.01 × Unused land area)/total area	+	--

Note: The total value of ecological services was calculated according to the ecological service value calculation model proposed by Costanza et al., and the adjustment services and support services in the ecosystem service value coefficient table of different land use types in Jiangsu revised by Jiang et al. were selected [58].

Based on the connotation of PLEF, this study referred the previous studies on the evaluation of PLEF, combining the geographical characteristics of each county in Jiangsu, then constructed an evaluation index system of PLEF in Jiangsu. The indicators were primarily selected following the principles of data availability and representativeness of indicators. Finally, 3 primary indicators and 14 secondary indicators were selected to establish the evaluation index system, as shown in Table 4.

Table 4. Indicators and weights for assessing production–living–ecological functions.

Criteria	Basic Level Indicator	Direction	Unit	Weight
Production function Index	Per unit area yield of grain	+	Ton/ha	0.201
	Per capita arable land	+	m^2/person	0.200
	Land reclamation rate	+	%	0.202
	Per capita output value of primary industry	+	10^4 yuan/person	0.199
	Per capita output value of the secondary industry	+	10^4 yuan/person	0.197
Living function Index	Density of road network	+	km/km^2	0.201
	Per capita retail sales of consumer goods	+	10^4 yuan/person	0.199
	Proportion of construction land	+	%	0.201
	Per capita household electricity consumption	+	10^4 kw·h/person	0.199
	Per capita public budget expenditure	+	10^4 yuan/person	0.200
Ecological function Index	Agricultural fertilizer input intensity	-	Ton/ha	0.254
	Green coverage ratio	+	%	0.241
	Ecological service value per unit area	+	10^8 yuan/ha	0.251
	Habitat quality index	+	--	0.254

2.3. Analysis Methods

2.3.1. Pre-Processing and the Entropy Weight Method

Due to the different units of the selected indicators, in order to avoid errors caused by the data units on the evaluation results, the data of each index were first dimensionlessly standardized. Depending on the properties of the indicator, the normalized approach is divided into two categories:

$$\text{Positive indicator}: X'_{ij} = \frac{X_{ij} - min(X_{1j}, X_{2j}, \ldots\ldots, X_{nj})}{max(X_{1j}, X_{2j}, \ldots\ldots, X_{nj}) - min(X1j, X2j, \ldots\ldots, Xnj)},$$

$$\text{Negative indicator}: X'_{ij} = \frac{max(X_{1j}, X_{2j}, \ldots\ldots, X_{nj}) - X_{ij}}{max(X_{1j}, X_{2j}, \ldots\ldots, X_{nj}) - min(X_{1j}, X_{2j}, \ldots\ldots, X_{nj})},$$

where X'_{ij} refers to the normalized value of the indicator; and X_{ij} refers to the original value of jth indicator in year i.

In this study, the entropy weighting method was chosen to determine the weight of each indicator, which is an objective weighting method that has been widely used in various fields [59,60]. For a certain indicator, the entropy value could be used to determine the degree of dispersion of the indicator. The smaller the entropy value of its information, the greater the degree of dispersion of the indicator, and the greater the influence (i.e., weight) of the indicator on the comprehensive evaluation [61]. This goes some way to avoiding the influence of subjectivity on the outcome of decisions. The formula is as follows:

$$p_{ij} = \frac{X'_{ij}}{\sum_{i=1}^{n} \boldsymbol{X'_{ij}}},$$

$$E_j = -ln(n)^{-1} \sum_{i=1}^{n} p_{ij} ln p_{ij},$$

$$W_j = \frac{1 - E_j}{k - \sum_{j=1}^{k} \boldsymbol{E_j}} (j = 1,\ 2, \ldots, k).$$

The calculation of weights was shown below, and the results of the weights were shown in Table 4. Finally, the individual function scores of PLEF can be calculated with the standardized data X'_{ij} and the entropy weight.

2.3.2. Analysis of the Coupling and Coordination of Functions

The coupling coordination model uses the coupling degree to explain the inter-relationship between several subsystems and further uses the coupling coordination degree to comprehensively evaluate and study the whole system. It is a research tool that could make a valid evaluation of overall balanced development [40]. In the current research, there have been some misunderstandings surrounding the model, leading to several errors in the conclusions. These misuses of the model might result from both inaccurate formulae and inappropriate interpretations of standard methods. Researchers typically use the average distribution to classify and explain non-average distributed values. However, the overconcentration of the coupling degree values might significantly undermine the validity of the research conclusions [53]. Therefore, we used the modified CCDM for the calculation. The revised model could increase the differentiation of coupling degree and thus have greater validity in the field of social science research [53]. The coupling degree was calculated as follows:

$$C = \sqrt{[1 - \frac{\sqrt{(P - L)^2 + (P - E)^2 + (L - E)^2}}{3}] \times \sqrt{\frac{MIN(P, L, E)}{MAX(P, L, E)} \times \frac{MID(P, L, E)}{MAX(P, L, E)}}},$$

where C refers to the coupling degree of PLEF in each unit, $C \in [0, 1]$. A higher value of the coupling degree indicates a stronger inter-relationship between subsystems, and vice versa. P, L, and E represent the production, living, and ecological function scores, respectively.

Considering the actual situation and the existing research results and with reference to the results of previous studies [11], this paper classified the coupling degree among the PLEF in Jiangsu into the following four levels, as shown in Table 5.

Table 5. Classifications of coupling degree.

Coupling Degree (C)	Type	Characteristic
[0, 0.3]	Low-coupling stage	PLEF is in a gaming state during the low-coupling period. When C = 0, the three functions are uncoupled from each other, and the system is disordered.
(0.3, 0.6]	Antagonism stage	The interaction between the three functions is strengthened. The superior function becomes more powerful and even takes over the space of the other functions, thus weakening them.
(0.6, 0.8]	Break-in stage	These three functions are beginning to balance and collaborate with each other in a benign coupling.
(0.8, 1.0]	High-coupling stage	The benign coupling among the three is enhanced and ordered. When C = 1, the three functions achieve benign resonant coupling, and the system converges to a new ordered structure.

In order to further study the specific coupling and coordination relationship among PLEF, the coupling coordination degree was chosen for analysis in this paper. The coupling coordination degree was calculated as follows:

$$D = \sqrt{C \times T},$$

where D and C refer to the coupling coordination degree and coupling degree respectively; and T is the average of P, L, and E.

With reference to previous research [54], we classified the coupling coordination degree into ten categories from low to high, as shown in Table 6.

Table 6. Degree and type of coupling and coordination.

Coupling-Coordination Degree D(t)	Partition Threshold D(t)	Types of Coupling Coordination
Dysregulation–regression area	[0, 0.1]	Extreme disorder decline
	[0.1, 0.2]	Dysregulated decline
	[0.2, 0.3]	Moderated disorder decline
Transition–reconciliation area	[0.3, 0.4]	Mild disorder decline
	[0.4, 0.5]	Moribund decline
	[0.5, 0.6]	Barely coordinated development
Coordinated development area	[0.6, 0.7]	Primary coordination development
	[0.7, 0.8]	Intermediate-level coordinated development
	[0.8, 0.9]	Well-coordinated development
	[0.9, 1]	Quality coordinated development

3. Results

3.1. Evolution Pattern of Production–Living–Ecological Function

According to the comprehensive evaluation, the scores of PLEF of 53 counties in Jiangsu in 2010, 2015, and 2020 were measured, and the measured values were spatially linked with the spatial analysis units in vector format through ArcGIS 10.6 software to form the spatial distribution map of PLEF in Jiangsu in 2010, 2015, and 2020, as shown in Figures 3–5. The average value of each function and the number of counties in each stage is shown in Tables 7 and 8.

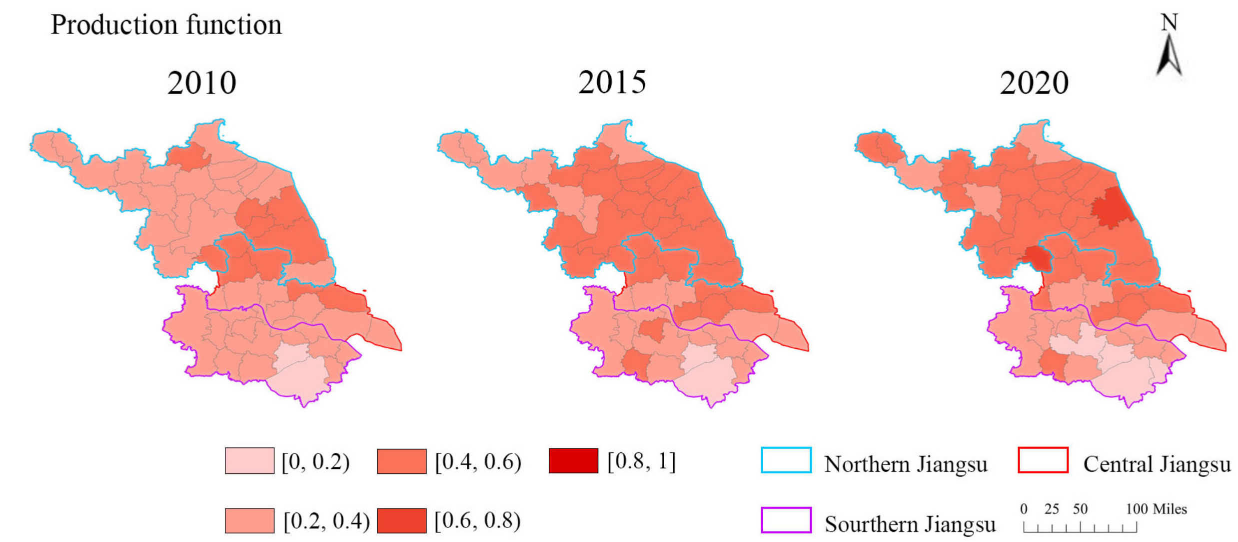

Figure 3. The spatial distribution of production function value.

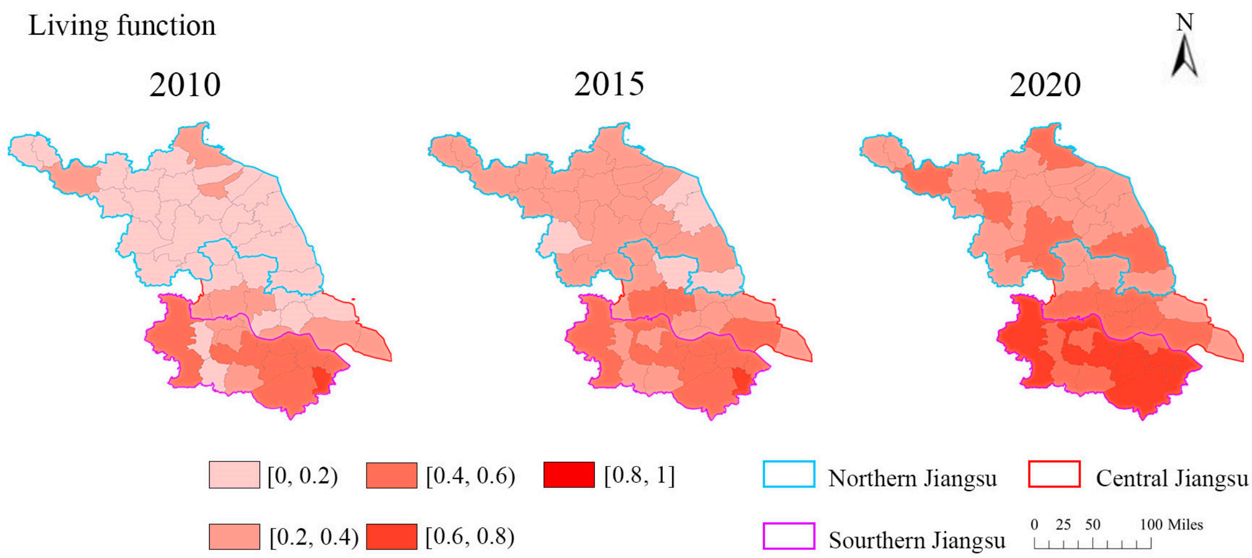

Figure 4. The spatial distribution of living function value.

Table 7. The average value of each function.

Category \ Year	2010	2015	2020
P	0.349	0.386	0.412
L	0.231	0.335	0.445
E	0.417	0.394	0.407

In general, the evolution of the PLEF was volatile: from 2010 to 2020, the production function steadily increased, the living function showed obvious signs of improvement, while the ecological function remained basically stable. Spatial divergence was diversified, with the production function declining in concentric circles, the living function differing significantly from north to south, and the ecological function having a scale-dependent effect of natural landscape.

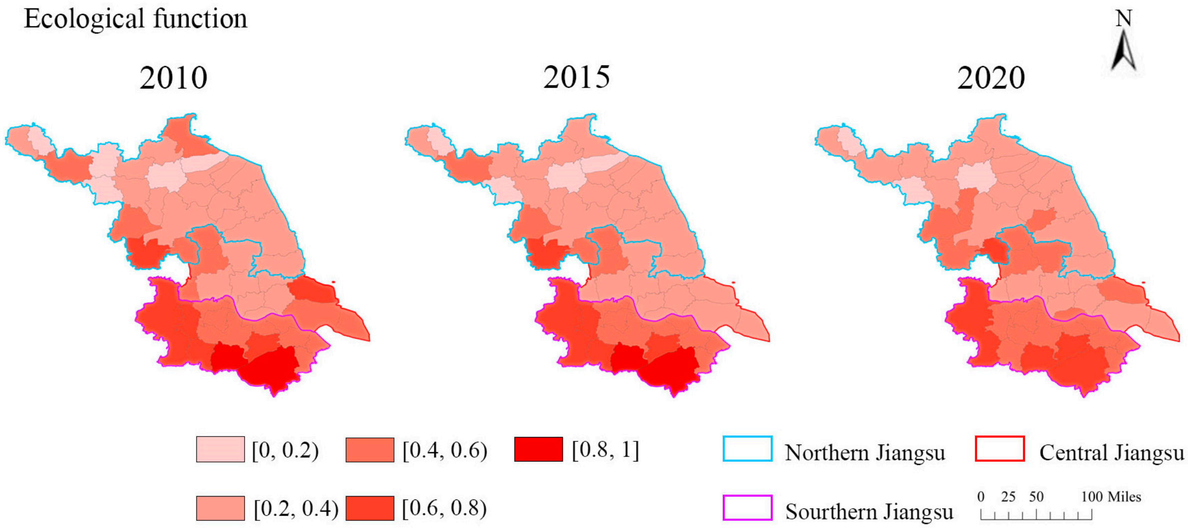

Figure 5. The spatial distribution of ecological function value.

Table 8. The number of counties in each stage.

	Production Function			**Living Function**			**Ecological Function**		
	2010	**2015**	**2020**	**2010**	**2015**	**2020**	**2010**	**2015**	**2020**
[0, 0.2]	2	2	4	31	5	0	5	4	3
[0.2, 0.4]	40	24	18	13	34	24	22	28	25
[0.4, 0.6]	11	27	29	8	13	19	18	14	20
[0.6, 0.8]	0	0	2	1	1	10	6	5	5
[0.8, 1]	0	0	0	0	0	0	2	2	0

3.1.1. Features of Spatial and Temporal Differentiation of Production Function

In terms of the spatial pattern, the production function showed an overall distribution pattern of being high in central Jiangsu and being low in the north and south. In 2010, Suzhou and Wuxi in the Taihu Lake basin were at the lowest values of production function, which was less than 0.2. The coastal county of Rudong was at the maximum value of the production function at 0.475. In 2015, nearly half of the districts had production function values between 0.4 and 0.6, and Jinhu had the highest production function value at that time of 0.529. However, the production function values of Suzhou and Wuxi were still lower than 0.2 and showed a further decreasing trend. By 2020, the overall layout of the production function in Jiangsu had changed little. The production functions of Jinhu and Sheyang steadily improved to above 0.6, but the production function of Kunshan and Changzhou, which are close to Suzhou and Wuxi, fell below 0.2.

In terms of temporal trends, the production function of the study area as a whole showed a gradual increase, with the mean value of the production function rising from 0.349 to 0.389 and finally to 0.412. The development trend in central Jiangsu outperformed that of southern and northern Jiangsu. During the study period, the number of areas with production function values between 0.2 and 0.4 steadily declined from 40 to 24 and finally to 18, while the number of areas with production function values between 0.4 and 0.6 showed a gradual expansion from 11 to 27 and finally to 29. Jinhu County and Sheyang County were upgraded to areas with production function values between 0.6 and 0.8 at the end of the study period. However, the lowest value of the production function fell from 0.118 to 0.082, and the number of areas with production function values between 0 and 0.2 has risen from 2 to 4, showing a bifurcation.

3.1.2. Features of Spatial and Temporal Differentiation of Living Function

In terms of the spatial distribution, the distribution of living function showed a decreasing pattern from south to north, with significant regional differences. The score of living function in the southern part of Jiangsu is much higher than that in the northern part, which showed a similar distribution pattern with the level of socioeconomic development. In 2010, almost all of the living function values in northern and central Jiangsu were below 0.2, with the lowest in Dongtai at only 0.056. At this time, in nearly half of southern Jiangsu, the values of the living function were more than 0.4, and sometimes considerably more, as in the case of Kunshan reaching 0.738, which was 13 times that of Dongtai. The average living function was just 0.231 in 2010. In 2015, almost all regions had improved their living functions to above 0.2, with only four counties—Binhai, Sheyang, Dongtai, and Sihong—still below 0.2. Despite this, only one-third of the counties in Jiangsu reached 0.4 or more, and Kunshan was still the only area with a living function of 0.6 or higher. However, the difference between the highest and lowest values was only 4 times. At this point, the provincial average of the living function rose 1.5 times to 0.335. By 2020, there had been a significant improvement in the whole province. All areas with the living function below 0.2 had disappeared. The number of districts with the living function of 0.4 or more reached 29, while the number of districts with the living function of 0.6 or more reached 10. The gap between the maximum and minimum values narrowed further, with a difference of only 3-fold.

In terms of temporal trends, the living function of the study area as a whole showed a clear upward trend, with the mean living function almost doubling from 0.231 to 0.335 and finally to 0.446. At the end of the study period, all areas had a living function above 0.2 and even reached a maximum of 0.753. Most of the areas improved their living function scores by one or two levels. While all living functions in the province were trending upward, the magnitude of the increase varied. For instance, the minimum value increased from 0.056 to 0.223, a 4-fold increase, but the maximum value barely increased at all.

3.1.3. Features of Spatial and Temporal Differentiation of Ecological Function

In terms of the spatial distribution, the ecological function scores were similar to the living function scores, with an overall decreasing distribution pattern from south to north. In 2010, the vast majority of areas had ecological function scores between 0.2–0.4 and 0.4–0.6. There were eight areas with ecological function scores greater than 0.6, two of which were above 0.8. The maximum value was 0.848 for Yixing, and the minimum value was 0.086 for Guanyun. There was a 10-fold difference between them. In 2015, Pizhou, which used to have an ecological function value below 0.2, was ranked above 0.2 for the first time, while Peixian, Guanyun, Suining, and Shuyang were still below 0.2. Meanwhile, the ecological function value of Rudong, which used to be above 0.6, unexpectedly dropped to 0.381. The provincial minimum improved from 0.086 to 0.136, but the average dropped from 0.417 to 0.394. By 2020, Guanyun, in the low-value area, removed the below 0.2 ranks, but Liyang, Xuyi, and Jurong, in the high-value area, dumped the above 0.6 ranks. In addition, the maximum value also decreased from 0.847 to 0.784. The average recovered from 0.394 in 2015 to 0.407 in 2020, but it was still less than the value of 0.417 at the beginning of the study period. Looking at it from a comprehensive point of view, the high-value areas were mainly located in the Taihu Lake basin, which was attributed to the dense water network and the abundance of wetlands in the area. The low-value areas were mainly concentrated in the northwestern counties, where there were many reclaimed mines and greater environmental pollution [56]. The temporal trends showed little overall change in the ecological function scores, with the mean values fluctuating between 0.39 and 0.41.

3.2. Coupling Coordination Characteristics of Production–Living–Ecological Function

3.2.1. Features of Spatial and Temporal Differentiation of Coupling Degree

According to CCDM, the coupling degrees of 53 districts in Jiangsu in 2010, 2015, and 2020 were measured, respectively. The measured values were spatially linked with the spatial analysis units in vector format via ArcGIS 10.6 software to form the spatial distribution of the coupling degree of the PLEF in Jiangsu in 2010, 2015, and 2020, as shown in Figure 6.

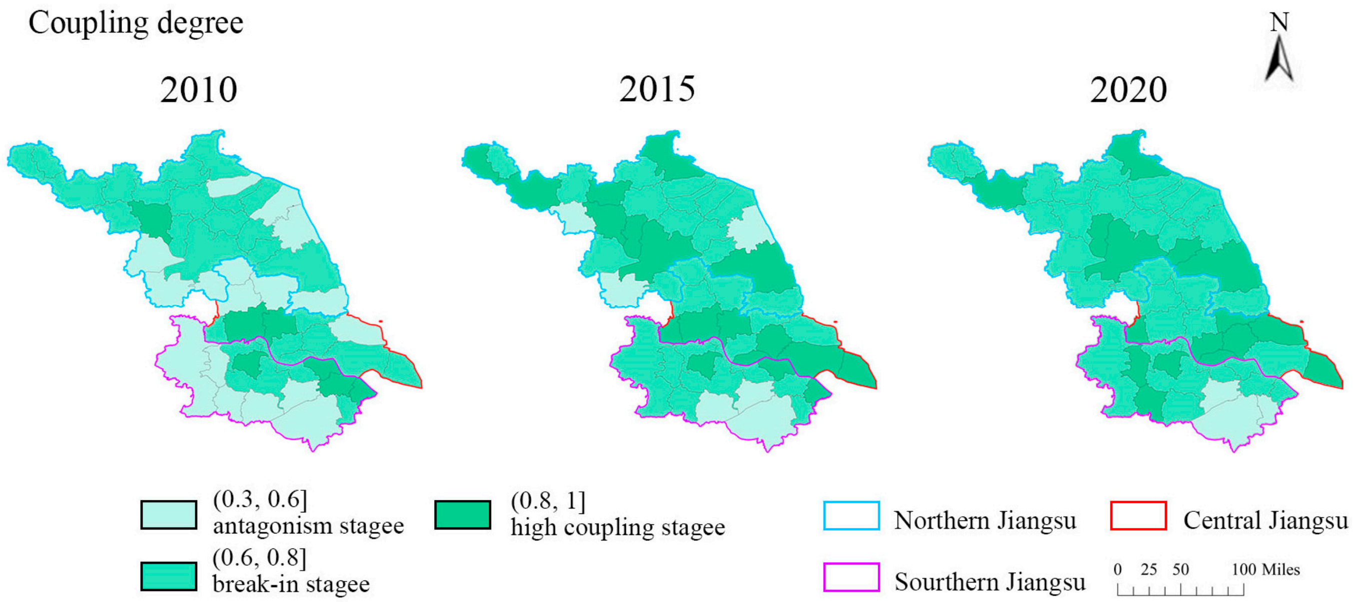

Figure 6. The spatial distribution of coupling degree of PLEF.

It could be seen that the coupling degree of PLEF in Jiangsu included three types: the antagonism stage, break-in stage, and high-coupling stage. During the study period, more than half of the districts were in the break-in stage. However, there was significant spatial and temporal heterogeneity in the coupling relationship between the PLEF.

In terms of spatial distribution, the high- and low-coupling areas were scattered. In general, northern and central Jiangsu were mostly in the break-in stage and high-coupling stage, while southern Jiangsu tended more towards the antagonism stage. The overall spatial pattern of the coupling degree was characterized by a high north to low south pattern. In 2010, the lowest coupling degree was 0.373 in Suzhou, and the highest was 0.937 in Yangzhou. In 2015, the lowest coupling degree was 0.361 in Suzhou, and the highest was 0.980 in Danyang. In 2020, the lowest coupling degree was 0.390 in Suzhou, and the highest was 0.968 in Yizheng. It was worth noting that both the maximum and minimum values in the province occurred in Southern Jiangsu, which was different from the PLEF, showing a large north–south difference.

The temporal trend showed a steady increase in coupling across counties, with the mean value rising from 0.667 to 0.745. However, there were some counties where the evolution of the coupling degree of PLEF was markedly volatile; for example, Xinyi entered the high-coupling stage from the break-in stage but returned to the break-in stage at the end of the study period; Liyang entered the break-in stage from the antagonism stage during the study period and finally entered the high-coupling stage; Kunshan retreated from the break-in stage to the antagonism stage.

By means of frequency analysis, the proportion of each coupling type in the same time period was calculated in groups according to the criteria of classifying coupling types, and the evolution curves of the coupling degree of the PLEF in 2010, 2015, and 2020 were fitted, respectively, as shown in the Figure 7.

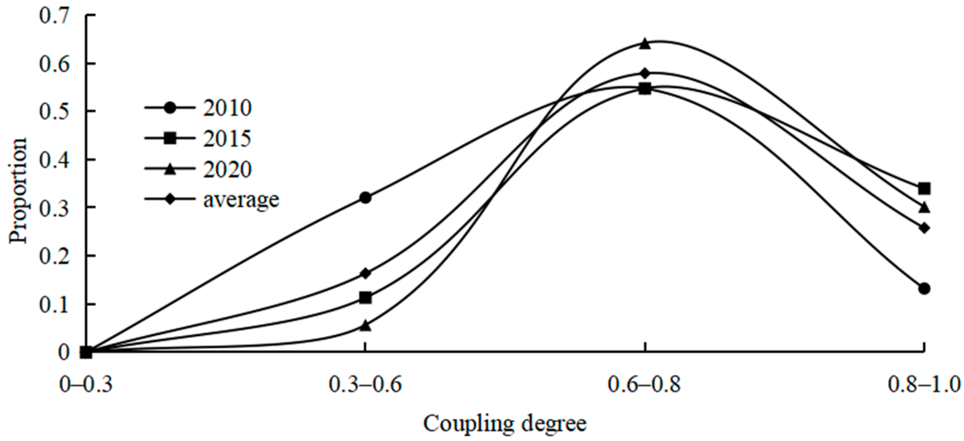

Figure 7. The evolution curve of the coupling degree of PLEF.

The evolution of the coupling degree of the PLEF in Jiangsu from 2010 to 2020 was close to an "S"-shaped growth curve. After a certain period undergoing polarization effect and diffusion effect, the interaction between the PLEF gradually evolved from the low-coupling stage to the coordinated coupling stage [62]. The number of counties in the antagonism stage had decreased. These decreases were shifted to the break-in stage and the high-coupling stage, where the increase was more pronounced in the high-coupling stage. However, despite this, over half of the areas were still in the break-in stage, and there was still potential for improvement.

3.2.2. Features of Spatial and Temporal Differentiation of Coupling Coordination Degree

According to CCDM, the coupling coordination degree values of 53 districts in Jiangsu in 2010, 2015, and 2020 were measured, respectively, and the measured values were spatially linked with the spatial analysis units in a vector format via ArcGIS 10.6 software to form the spatial distribution of the coupling coordination degree of the PLEF in Jiangsu in 2010, 2015, and 2020, which is as shown in Figure 8.

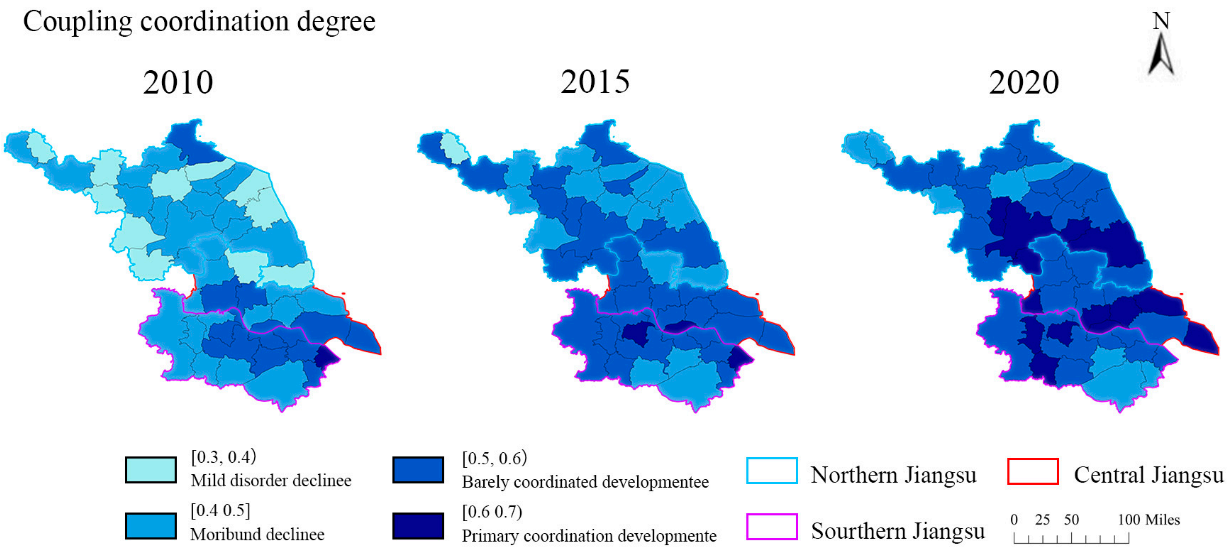

Figure 8. The spatial distribution of the coupling coordination degree of PLEF.

In the spatial dimension, there was a correlation between the coupling coordination degree of the PLEF in Jiangsu and the spatial distribution of its coupling degree. However, the spatial differences were a little more pronounced than the latter. At the beginning of the study period, the coupling coordination degree tended to be low in areas with a high coupling degree and vice versa. However, at the end of the study period, the high-value areas with respect to the coupling coordination degree and the coupling degree largely coincided. Eventually, a spatial pattern of high-value zones was formed, with the junction zone of north and central Jiangsu and the junction zone of central and south Jiangsu being the high-value zone.

In the temporal dimension, the coupling coordination degree showed a gradual increase from moribund decline to barely coordinated development, with the average level of the coupling coordination degree increasing from 0.465 to 0.557. In 2010, the coupling coordination degree was between 0.318 (Guanyun) and 0.625 (Taicang). The main types of coupling coordination were mild disorder decline, moribund decline, barely coordinated development, and primary coordinated development, accounting for 20.75%, 50.94%, 26.42%, and 1.89%, respectively. In 2015, the coupling coordination degree was between 0.392 (Peixian) and 0.628 (Danyang). The types of coupling coordination in this period were consistent with 2010, i.e., mainly mild disorder decline, moribund decline, barely coordinated development, and primary coordinated development, accounting for 1.89%, 30.19%, 62.26%, and 5.67%, respectively. The overall level had improved by one stage from the previous period, with a significant reduction in the proportion of mild disorder decline and an increase in both barely coordinated development and primary coordinated development. As a result, the average of the coupling coordination degree was higher in this period than in 2010, but the rise was not significant. In 2020, the coupling coordination degree was between 0.438 (Suzhou) and 0.664 (Jinhu). During this period, the coupling coordination type of mild disorder decline was no longer present. In addition, moribund decline, barely coordinated development, and primarily coordinated development accounted for 15.09%, 58.49%, and 26.42%, respectively. The overall level of the coupling coordination degree in this period had improved compared to 2015, but it was still at the barely coordinated development stage.

The evolution curves of the coupling coordination degree of the PLEF in 2010, 2015, and 2020 are shown in Figure 9. As can be seen from the graph, the coupling coordination degree was in a state of fluctuating growth, with the greatest increase occurring in the barely coordinated development phase. The increase in the barely coordinated development phase came mainly from the decrease in moribund decline phase. The changes in the other two phases were relatively less dramatic. The overall level of the coupling coordination degree was lower and grew more slowly than the coupling degree. However, according to the trend of the curve, it can be presumed that with the passage of time, the coupling coordination of the PLEF in Jiangsu would gradually evolve to a higher stage, i.e., in line with the future development trend of the coupling degree, and the development of the PLEF would be more coordinated and orderly.

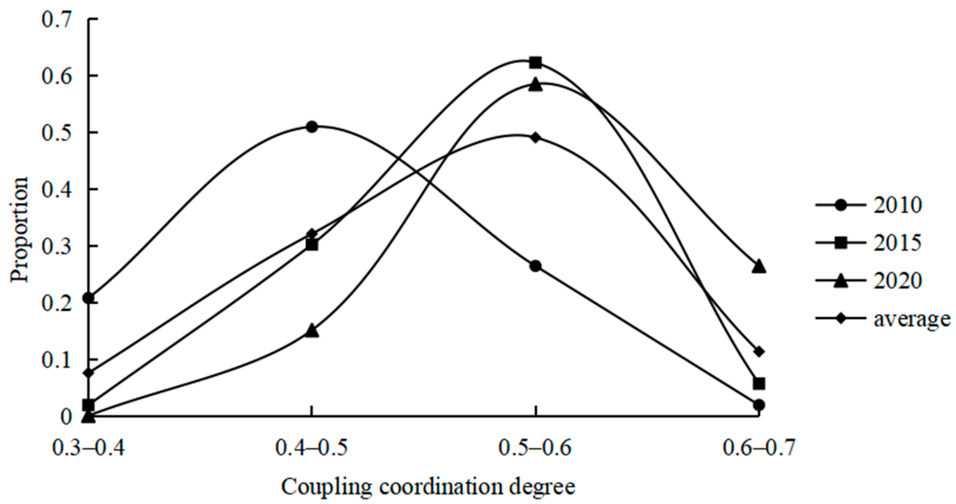

Figure 9. The evolution curve of coupling coordination degree of PLEF.

4. Discussion

Exploring the coupling and coordinated relationship among production, living, and ecological functions in land space was the key to optimizing the spatial allocation of land in Jiangsu and promoting coordinated and sustainable development. This study measured the development status of PLEF and their coupling and coordinated relationship in 2010, 2015, and 2020, respectively, through an improved CCDM, and used GIS spatial analysis to reveal their spatial and temporal evolution patterns, providing a new perspective from which to clarify the interactions among PLEF in Jiangsu, which had certain reference significance for optimizing land use in Jiangsu. An improved CCDM provides new research perspectives not only for PLEF research but even new protocols for other fields.

Due to the non-equilibrium, dynamics, and complexity of the interaction among production, living, and ecological functions, the PLEF was characterized by strong spatial heterogeneity and uncertainty [63]. The results of the study also confirmed this inference. The reasons of this study are mainly influenced by natural resource endowments, socioeconomic development, and regional policies [57]. First, one of the most prominent factors shaping the living function is undoubtedly socioeconomic development; the more economically developed a region is, the higher the government revenues, as well as the personal incomes, tend to be. Increased government revenues enable more robust infrastructure development, public service facilities, and enhanced social welfare provisions [64]. Simultaneously, heightened personal incomes encourage individuals to engage in increased consumption, consequently fueling economic growth [65,66]. Meanwhile, economic construction is the focus of the Chinese government, and economic performance is an important assessment criterion for local governments. As a result, local governments will spare no effort to develop their economies, which has led to a situation where most of the production and living functions of the counties appear to be upgraded (0.349 to 0.412). From an international perspective, similar trends can be observed in various developing and developed nations where economic growth significantly impacts the development of infrastructure, public services, and social welfare programs [67,68]. This phenomenon highlights the globally recognized role of economic prosperity in shaping the overall quality of life and living standards within a region. The spatial distribution of living function in each county of Jiangsu is just like its level of economic development, i.e., decreasing from the south to the north (Figure 3). On the other hand, production and ecological functions are more limited by natural resource endowments and regional policy influences, as they are more dependent on their background resource conditions. The high level of urbanization and high population density in southern Jiangsu makes it inevitable that agricultural and ecological land will be squeezed by construction land. Central Jiangsu has a reasonable industrial structure, convenient transportation, close urban–rural links, and its township industries and agriculture are strongly driven. However, the northern part of Jiangsu started urbanization later than the southern, which has weak non-agricultural production capacity, low socioeconomic productivity, and lacks the pulling point to enhance the overall production capacity [69]. At the same time, due to the implementation of the policy of arable land occupation and compensation, the economically developed areas of arable land indicators were transferred to economically underdeveloped areas. This further squeezed the agricultural production capacity of southern Jiangsu (economically developed areas) and the non-agricultural production capacity of northern Jiangsu (economically underdeveloped areas) [70,71]. These resulted in a lower production function in the north and south than in the central region.

For the ecological function, this depends to a greater extent on the fulfillment of ecological landscape background functions. The middle and lower reaches of the Yangtze River have a denser water network and more wetlands, and the ecological function is spatially dependent on the mountains and the water. Moreover, northern Jiangsu has a lot of reclaimed mines and greater environmental pollution. This largely determined the value of ecological services and thus the overall ecological functioning score (Figure 5). Internationally, scholars have pointed out that as economic levels rise, government attitudes towards environmental protection change, which results in environmental conditions deteriorating before improving. This is especially true in countries where government dominance is stronger [72]. In 2012, the Chinese government put forward the concept of "ecological civilization construction" for the first time, which marked the beginning of China's advocacy of coordinating the relationship between economic development and ecological protection [73]. It realizes the benign interaction among the PLEF through territorial spatial planning and a certain ecological compensation, and it expects the PLEF to gradually move towards a highly coupled stage of order and coordination. It is based on these factors that the distribution of PLEF showed such heterogeneity and uncertainty.

The spatial heterogeneity of PLEF inevitably leads to heterogeneity in their coupling and coordination relationships as well. The spatial distribution of the coupling degree in the study area is initially characterized as higher in the north and lower in the south, while the opposite is true for the coordination degree. This disparity could be attributed to the notably higher living function (relative to other functions) in southern Jiangsu at the early stages of the study, as the larger differences between the PLEFs resulted in less coupling. However, this high living function value, in turn, contributes to the higher mean value of its PLEF, which is the important component of the coupling coordinated degree. So, the coupling coordination degree temporarily demonstrated an inverse relationship with the coupling degree (Figures 6 and 8). However, over time, the spatial patterns of the coupling degree and the coupling coordination degree gradually converged. Eventually, a spatial pattern was formed with the regional junction zone as the high-value area. This was also caused by the difference in PLEF. Areas with large differences between PLEF had a high average PLEF, and those with small differences between PLEF had relatively low means. From a temporal perspective, the evolution curve of the coupling degree exhibited an "S" shape, while the coupling coordinated degree demonstrated fluctuations across the study area, which is also consistent with the findings of Yang et al. [11]. The curve trend reveals that Jiangsu is growing in a more coordinated direction. However, there are still a few counties, such as Kunshan, that have regressed from the Break-in stage to the Antagonism stage. The reason for this might be that the implementation of the policy of arable land occupation and compensation had made it legally justifiable to appropriately squeeze the production function. Moreover, such an operation could greatly improve the local economic efficiency, which is also a situation that local governments want to see [65]. Because there is room for the expansion of living function, the ecological environment is relatively less occupied. As a result, the conflict between production and living functions in Kunshan has become more intense, while the ecological function has been able to remain relatively stable, which has led to a regression in its coupling relationship.

Previous studies have tended to focus on analyzing the coupling relationships of the two among the three, which inevitably led to the neglect of the third function. To address this issue, all three subsystems need to be studied in depth to fully understand their interactions and dependencies. In some studies of more subsystems, even a fully integrated coupling analysis of all subsystems is required [74]. After synthesizing the overall coupling coordination relationships, we found that differentiated development strategies should be implemented according to the different regional types. In southern Jiangsu, where the living function is more complete and the ecological function holds a dominant position, economic development and ecological protection will squeeze and coerce the production space, resulting in a lower production function score, thus affecting the coupling and coordination relationship among the PLEF. Thus, it becomes imperative to shift focus towards safeguarding fundamental agricultural land, which often receives less attention compared to the prominent emphasis on ecological preservation. However, in the northern part of Jiangsu, where there is a lot of agricultural land, the restrictions of the arable land red line and the ecological pressure will squeeze the living space, so it is necessary to optimize the production function while taking into account the harmonious development of the living and ecological functions. Internationally, analogous challenges have been observed, particularly in regions where the balance between economic development, ecological preservation, and sustainable agriculture is delicate. Various countries have implemented integrated strategies that prioritize the preservation of agricultural land while simultaneously ensuring sustainable economic growth and ecological conservation [75,76]. Such global perspectives underscore the significance of comprehensive planning that accounts for the interplay among the production, living, and ecological functions, considering the unique contextual demands of each region. Nowadays, the government has come to realize the problem in this area. It can be hypothesized that over time, the coupling of the PLEF in Jiangsu will gradually evolve from a low-coupling stage to a high-coupling stage. Consistent with future trends in the coupling degree, the development of the PLEF will become more harmonized.

The coupling degree and coupling coordination degree were measures of the inter-relationships among the subsystems, and their overall upward trend indicated that the PLEF showed a tendency to converge and to a higher level. At the same time, the results obtained from the modified model made the regional differences more pronounced. This is more meaningful with respect to the formulation of specific policies by the relevant departments. The study's coupling coordination degree was distributed between 0.3 and 0.7, while some studies' coupling coordination degree was basically in the range of 0.45–0.55 [40]. The same is true for the coupling degree, which was measured in this study to cover 0.3–1, while some studies had measured coupling degree as basically above 0.9 [54]. Too small a difference in the coupling degree and coupling coordination degree between study regions might lead to low validity of the final results. This might ultimately limit the demonstration of the value of the research. The overly centralized coupling degree or coupling coordination degree might be due to the differences in the research areas or subsystems. However, the modified model does indeed bring us a new perspective on coupling studies, on which deeper related studies could be based in the future. The improved model can assess the inter-relationships among subsystems more precisely and effectively, which provides a more scientific reference for the overall analysis of multi-system objects. It is of greater significance not only for the PLEF field but also for other fields or multi-dimensional studies that study large-scale spatial coupling relationships, such as low-carbon development and urbanization [77], water resource spatial equilibrium [78] and chemical ecology [79], etc.

However, limitations in the data collection and quantification methods mean that the measured coupling coordination degree is only relative to this study period and within this study area; it is not absolute. At the same time, there is inevitably a certain degree of subjectivity in the construction of the indicator system. These make it difficult to compare the results of different researchers. Therefore, the selection of indicators in future studies could be referred to theoretical analysis or other, better methods. Finally, although the coupling and coordinated relationship among the PLEF has been studied in this study, their inter-transformation needs to be further elaborated in subsequent studies.

5. Conclusions

In order to comprehensively optimize the spatial configuration and promote the coordinated and sustainable development of the national territory, this study takes Jiangsu Province as an example and adopts the modified CCDM to conduct an in-depth quantitative analysis of the PLEF and its coupling coordination relationship in rapidly urbanizing areas. The following conclusions of this research were obtained: (1) The spatial and temporal divergence of the three functions in Jiangsu was obvious. From a temporal perspective, the scores for the production and living functions had steadily increased, while the scores for the ecological function fluctuated slightly. Spatially, the production function scores were high in the center and low in the north and south, while the living and ecological function scores were shown to be decreasing from south to north. (2) The coupling degree initially showed a spatial distribution of being high in the north and low in the south but eventually formed a spatial pattern with the junction zones of north and central Jiangsu and central and south Jiangsu as the high-value zones. The temporal evolution was close to an "S"-shaped growth curve, and the counties gradually developed from a low-coupling stage to a coordinated coupling stage. (3) The coupling coordination degree was initially opposite to the spatial distribution of coupling degree, showing a spatial distribution of being high in the south and low in the north. However, eventually, like the coupling degree, it formed a spatial pattern with the junction zones of north and central Jiangsu and central and south Jiangsu as the high-value areas. The evolution curve showed a wave-shaped upward trend. (4) Differentiated development strategies should be implemented according to the law of coupling and coordinated evolution and different regional characteristics.

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