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Coupling coordination analysis of water-energy-food-ecology in the Yangtze River Delta

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ABSTRACT

Water, energy, food, and ecology are essential for human survival and development. The Yangtze River Delta is one of the most important regions for China's sustainable development. It is of great significance to study the coupling coordinated development level of water-energy-food-ecology in the Yangtze River Delta for sustainable development. In this study, we establish the water-energy-food-ecology (WEFE) coupling and coordination development index system. Then, we analyze the degree of coupling coordination (DCC) of WEFE based on the coupling coordination evaluation model and projection pursuit model. The results show that the DCC of WEFE in the Yangtze River Delta shows obvious spatial-temporal characteristics. From the temporal view, the DCC in the Yangtze River Delta has shown an upward trend; from the spatial view, the DCC of Jiangsu, Anhui, and Zhejiang is higher than that of Shanghai.

Key words: coupling coordination, projection pursuit, water-energy-food-ecology, Yangtze River Delta

HIGHLIGHTS

- Water, energy, food, and ecology are essential for human survival and development.
- It is of great significance to study the coordinated development level of WEFE in the Yangtze River Delta.
- The coupling coordination degree of WEFE in the Yangtze River Delta shows obvious spatial-temporal characteristics.
- The coupling coordination degrees in the Yangtze River Delta are gradually increasing in recent years.

1. INTRODUCTION

The Yangtze River Delta is one of the most important economically developed regions in China. With the rapid growth of the economy, it is facing problems such as water crisis, energy shortage, food security, environmental pollution, and ecosystem damage. For a long time, high-intensity consumption of resources promotes economic growth, but it has also caused pollution of the ecological environment and constrained the sustainable development of the economy, resulting in the contradiction between water resources, energy, food, and the ecological environment. How to realize the coordinated development of water-energy-food-ecology (WEFE) has become an important topic of current research (Lu *et al.* 2017).

Focused on the dual-sector interactions of water, energy, food, and ecology, scholars have taken a series of research. For example, Ouyang *et al.* (2021) discussed the relationship between water resource consumption and food production; Liu *et al.* (2022) analyzed the coordination between ecology and economy; Deng *et al.* (2021) discussed the coupling coordination between ecology and economic development; However, water, energy, food, and ecology are inextricably intertwined, forming a complex and dynamic system (Ma *et al.* 2021). Thus, in recent years, scholars have taken the integrated analyses of cross-sectors.

The research on the connotation and mechanism of the WEFE system is constantly enriched and developed. It is changing from the initial theoretical framework research to quantitative empirical research with more practical value, and the corresponding research methods are further expanded and improved. The WEFE not only describes the interdependence among water, food, and energy sectors (Karabulut *et al.* 2016) but also considers the feedback effect of the ecosystem to seek solutions to achieve the maximum synergy among resources sectors (Zhang *et al.* 2019). In recent years, the academic community has examined the problems and risks of environmental management and economic development based on the WEFE framework and discussed frontier issues in the field of resource and environmental science, such as resource constraints in different regions (Shi *et al.* 2019), the resilience of the social ecosystem to external shocks (Liu & Chen 2020).

However, the analysis of coupling coordination of WEFE involves various factors. It is a high-dimension problem. The traditional methods can't resolve this issue well. The projection pursuit (PP) can deal with this problem effectively by projecting the high-dimension data into the low-dimension subspace. Therefore, this paper adopts PP and the coupling coordination model to calculate the degree of coupling coordination (DCC) of WEFE.

Thus, in this study, we propose an evaluation indicator system of WEFE in the Yangtze River Delta, based on the systematic analysis of the coordinated development mechanism of WEFE. On this basis, the coupling coordination degree model and the projection pursuit model are adopted to analyze the DCC of WEFE, to provide theoretical guidance for governments to make water, energy, food, and ecological policies.

2. MATERIALS AND METHODS

2.1. Study area

The Yangtze River Delta includes Shanghai, Anhui, Jiangsu, and Zhejiang (Figure 1). The research period spans from 2013 to 2019. The data are mainly from China Urban Statistical Yearbook (2013–2019), Shanghai Statistical Yearbook (2013–2019), Jiangsu Statistical Yearbook (2013–2019), Zhejiang Statistical Yearbook (2013–2019), and Anhui Statistical Yearbook (2013–2019). Some missing data are obtained by the moving average simulation method.

2.2. Indicator system of water-energy-food-ecology

Water-energy-food ecology is a complex and uncertain system. Energy provides power for water resources utilization and food production; water resource is the basic element for energy and food production; the utilization of water resources, energy, and food production affect the ecological environment. Thus, based on the coupling and coordination mechanism and relevant literature (Xiang 2017; Rong *et al.* 2019; Qin *et al.* 2022), water resource and energy subsystem mainly consider the total amount, structure, and efficiency indicators. In the water resource subsystem, the total water resources and total water consumption reflect the general situation of water resources; the proportion of water consumption of agricultural, industrial, ecological, and domestic users reflect the structure of water utilization; the water consumption per unit GDP and wastewater discharge of per unit GDP reflects the efficiency of water consumption. In the energy subsystem, the total

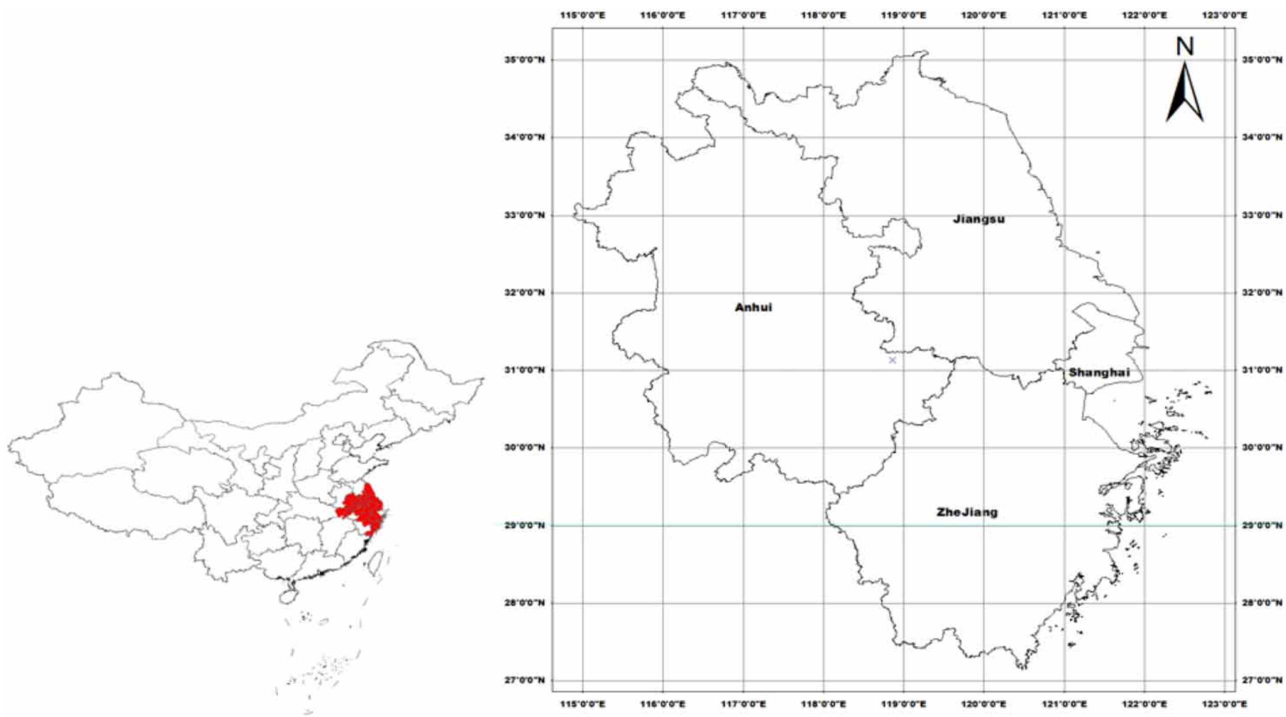

Figure 1 | Study area: Shanghai, Anhui, Jiangsu and Zhejiang in the Yangtze River Delta.

Table 1 | Indicator system of water-energy-food-ecology (WEFEIS)

System	Indicators	Symbol	Units	Plus-minus
Water subsystem	Total water resources	X10	Billion m^3	+
	Per capita water resources	X11	m^3	+
	Per capita water consumption	X12	m^3	−
	Total water consumption	X13	m^3	−
	Proportion of agricultural water consumption	X14	%	−
	Proportion of industrial water consumption	X15	%	−
	Proportion of ecological water consumption	X16	%	+
	Proportion of domestic water consumption	X17	%	−
	Water consumption per 10,000 yuan GDP	X18	m^3	−
	Wastewater discharge per unit GDP	X19	Ton/10,000 yuan	−
Energy subsystem	Energy consumption	X20	10,000 tons of coal	−
	Power generation of the whole province	X21	Billion kwh	+
	Proportion of agricultural energy consumption	X22	%	−
	Proportion of industrial energy consumption	X23	%	−
	Energy consumption per 10,000 yuan GDP	X24	10,000 tons of coal	−
	Wastewater discharge per unit GDP	X25	Ton/10,000 yuan	−
	Energy consumption of industrial added value	X26	Ton/10,000 yuan	−
	Energy conservation expenditure	X27	Billion yuan	+
Food subsystem	Affected area of crops	X30	Hectares	−
	Per capita grain output	X31	kg	+
	Growth rate of agricultural output	X32	%	+
	Total agricultural output	X33	RMB100 mn	+
Ecological subsystem	Air quality index (AQI)	X40	%	+
	Particulate matter (PM10)	X41	Microgram/m^3	−
	Environmental emergencies	X42	Frequency	−
	Proportion of class III water quality section	X43	%	+
	Investment in industrial pollution control	X44	10,000 yuan	+

energy consumption reflects the whole situation of energy consumption; the proportion of energy consumption of agriculture, and industries reflects the utilization structure of energy; the energy consumption pf per unit GDP, the energy consumption of industrial added value reflect the efficiency of energy. In the food subsystem, indicators about the security of food supply are mainly considered. Thus, the total agricultural output, the per capita grain output, and other indicators are considered. In the ecology subsystem, the indicators corresponding to water resources, energy, and food production and consumption are considered. Based on the above analysis, the WEFE coupling and coordination development index system (WEFEIS) is shown in Table 1.

2.3. Coupling and coordination model

Based on the water-energy-food-ecology indicator system (WEFEIS) proposed in the last subsection, we compute the comprehensive development level of each subsystem by the GA optimized projection pursuit model. Then, we assess the degree of coupling coordination (DCC) of the WEFE system in the Yangtze River Delta, based on the coupling coordination degree evaluation model.

2.3.1. Evaluation of development level based on projection pursuit

Projection pursuit (PP) can project the high-dimension data into low-dimensional space, which is effective in evaluating the comprehensive development level (CDL) of each subsystem in WEFE. Meanwhile, due to the genetic algorithm (GA) can find the optimization value based on the biological evolution law and genetic mechanism (Bradford *et al.* 2018; Sun & Khayatnezhad 2021). Therefore, we coupled GA and PP to calculate the CDL.

Suppose there are n samples with m indicators, $X = \{x_1^*, x_2^*, \cdots, x_m^*\}$, $x_j^* = \{x_{1j}^*, x_{2j}^*, \cdots, x_{nj}^*\}$ be the sample set, where x_{ij}^* is the value of j-the indicator of i-th sample. The PP can be calculated as follows:

- Data normalization.

To eliminate the different measurements of each indicator, we adopt the min-max standardization formula to normalize the data.

$$x_{ij} = \begin{cases} \dfrac{x_{ij}^* - \min x_j^*}{\max x_j^* - \min x_j^*}, & \text{if the indicator is positive,} \\ \dfrac{\max x_j^* - x_{ij}^*}{\max x_j^* - \min x_j^*}, & \text{if the indicator is negative.} \end{cases} \tag{1}$$

- Construct the projection indicator function.

For $i = 1, 2, \cdots, n$, let

$$z(i) = \sum_{j=1}^{m} a_j x_{ij} \tag{2}$$

where $a = (a_1, \cdots, a_m)$ is a unit length vector. Then, we calculate the standard deviation and local density of $z(i)$ as follows:

$$S_z = \sqrt{\frac{\sum_{i=1}^{n} [z(i) - E(z)]^2}{n-1}} \tag{3}$$

$$D_z = \sum_{i=1}^{n} \sum_{j=1}^{m} (R - r_{ij}) \cdot u(R - r_{ij}) \tag{4}$$

where $E(z)$ is the mean of $z(i)$, R is the windows radius of local density, r_{ij} is the distance between samples, $u(t)$ is the unit step function, that is, $u(t) = 1$ if $t \geq 0$, otherwise equals to 0.

- Optimize the projection indicator function.

For a given sample set, the projection directions corresponding to the projection indicator functions, and reflect the data structure or data characteristics. The optimization of the projection index function is to explore the maximized value. It can be derived by solving the following optimization problem:

$$\begin{aligned} \max \quad & Q(a) = S_z D_z \\ \text{s.t.} \quad & \sum_{j=1}^{m} a_j^2 = 1 \end{aligned} \tag{5}$$

In this study, due to the effectiveness in global optimization search, the GA was adopted to optimize the projection indicator function, and to explore the best projection direction.

- Calculate the comprehensive development level.

The optimal projection value $z^*(i)$ of each sample can be calculated by the formula (2) and the optimal projection direction a^* derived by (5). According to $z^*(i)$, the comprehensive development level (CDL) of subsystems will be obtained. Generally, the larger the $z^*(i)$, the higher the comprehensive development level.

The coupling coordination degree model can measure the coordinated degree of different subsystems. The processes of the model are as follows:

- Calculate the CDL of subsystems based on the coupled PP and GA models.

• Obtain the coupling degree of WEFE by the following formula:

$$C = n\frac{\sqrt[n]{f(x_1)\times f(x_2)\times\cdots\times f(x_n)}}{f(x_1)+f(x_2)+\cdots+f(x_n)} \tag{6}$$

where $f(x_i)$ is the CDL of each subsystem; $C \in [0, 1]$ is the coupling degree. However, the coupling degree can only reflect

Table 2 | The classification of the degree of coupling coordination

DCC Interval	DCC Grade	DCC Level
$(0 \sim 0.1)$	1	extreme imbalance
$(0.1 \sim 0.2)$	2	severe imbalance
$(0.2 \sim 0.3)$	3	moderate imbalance
$(0.3 \sim 0.4)$	4	mild imbalance
$(0.4 \sim 0.5)$	5	near imbalance
$(0.5 \sim 0.6)$	6	barely coupling coordination
$(0.6 \sim 0.7)$	7	primary coupling coordination
$(0.7 \sim 0.8)$	8	intermediate coupling coordination
$(0.8 \sim 0.9)$	9	good coupling coordination
$(0.9 \sim 1.0)$	10	high-quality coupling coordination

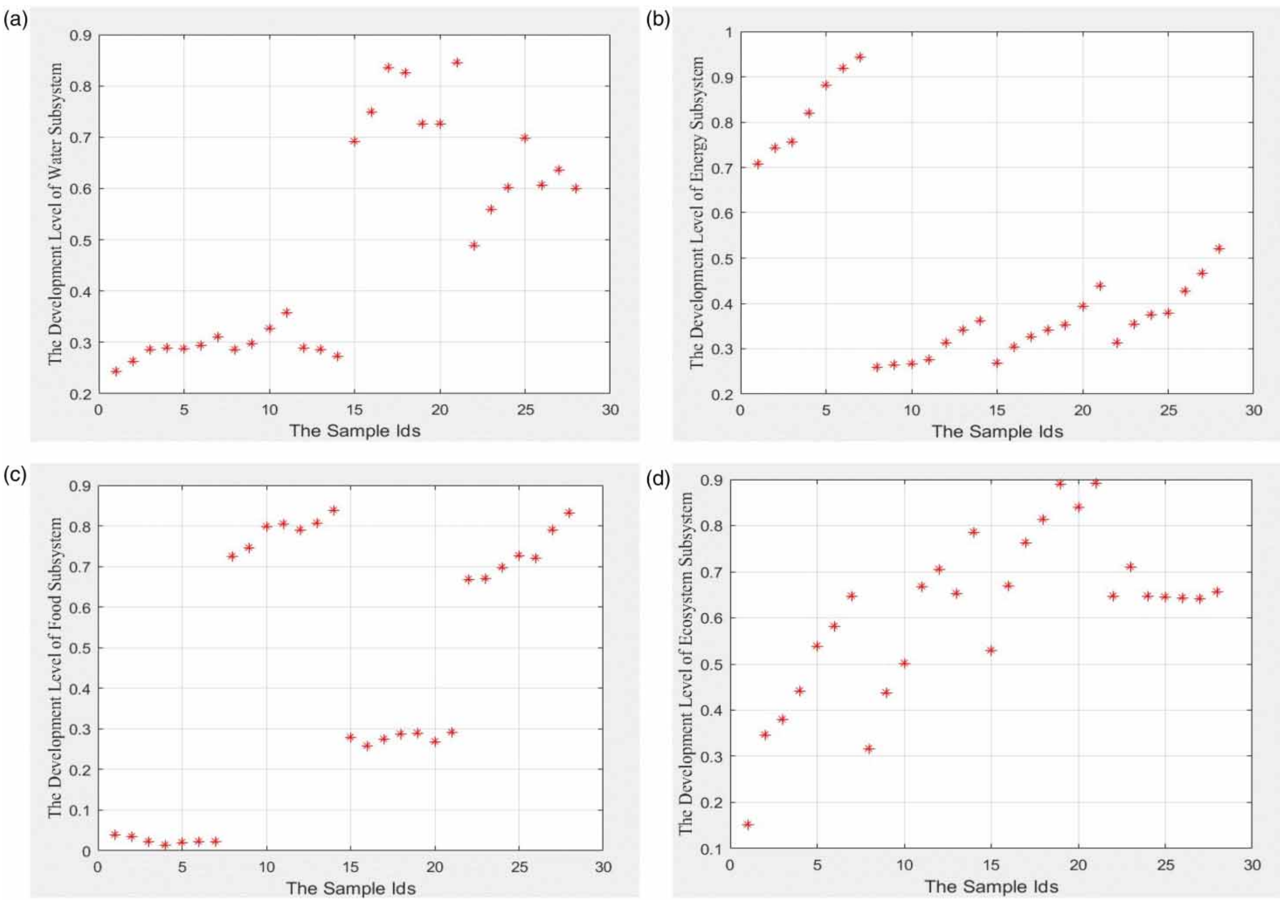

Figure 2 | Comrehensive development level (CDL) of each subsystem. (a) CDL of water subsystem, (b) CDL of energy subsystem, (c) CDL of food subsystem, (d) CDL of ecology subsystem.

the interaction degree of the subsystems, but cannot represent the coupling coordination level of different subsystems. Therefore, it's necessary to compute the coupling coordination degree of subsystems.

- Compute the degree of coupling coordination (DCC) of WEFE as follows:

$$T = a_1 f(x_1) + a_2 f(x_2) + \cdots + a_n f(x_n) \tag{7}$$

$$D = \sqrt{C \times T} \tag{8}$$

where D is the value of DCC, T is the comprehensive development level of WEFE, a_i is the weight of each subsystem. To reflect each subsytem farily, we set $a_i = 1/n$. The classification of DCC was shown in Table 2.

3. RESULTS AND DISCUSSION

3.1. The development level of subsystems

By using the method stated in Section 2.3.1, we have obtained the comprehensive development levels for each subsystem of WEFE. The results are plotted in Figure 2 and presented in Table 3.

The results indicate that, from 2013 to 2019, the development level of the water subsystem in Shanghai, Jiangsu, Zhejiang, and Anhui showed an upward trend, but it is obvious that the development level of Jiangsu and Shanghai is lower than that of Zhejiang and Anhui. From the historical data, the total amount and per capita share of water resources in Shanghai and Jiangsu are far lower than those in Zhejiang and Anhui. At the same time, the water consumption of 10,000 yuan GDP in Zhejiang is much higher than that in Jiangsu and Anhui. Although the water consumption and wastewater discharge of 10,000 yuan GDP in Shanghai maintain a good development level in three provinces and one city, the total amount of

Table 3 | Comprehensive development level for each subsystem of WEFE

Region	Year	Water subsystem	Energy subsystem	Food subsystem	Ecology subsystem
Shanghai	2013	0.24265	0.70742	0.03892	0.15071
	2014	0.2625	0.74249	0.03411	0.34588
	2015	0.28582	0.75622	0.02234	0.37869
	2016	0.28952	0.81953	0.01402	0.44173
	2017	0.28807	0.88155	0.01959	0.53754
	2018	0.29335	0.91832	0.02251	0.58123
	2019	0.31057	0.9439	0.02263	0.64703
Jiangsu	2013	0.28634	0.25839	0.72348	0.31549
	2014	0.29799	0.26457	0.74532	0.43753
	2015	0.32673	0.26607	0.7973	0.50085
	2016	0.35858	0.27483	0.80522	0.66768
	2017	0.2898	0.31236	0.79023	0.70539
	2018	0.28621	0.34187	0.80683	0.65200
	2019	0.27266	0.36228	0.83708	0.78577
Zhejiang	2013	0.69219	0.26891	0.27876	0.52888
	2014	0.74913	0.30342	0.25660	0.66976
	2015	0.83560	0.32557	0.27501	0.76336
	2016	0.82496	0.34192	0.28682	0.81331
	2017	0.7258	0.35307	0.28830	0.89026
	2018	0.7263	0.39349	0.26765	0.83856
	2019	0.84491	0.43901	0.2902	0.89154
Anhui	2013	0.48906	0.31318	0.667	0.64684
	2014	0.55951	0.35366	0.67061	0.71079
	2015	0.60094	0.37456	0.69683	0.64693
	2016	0.69730	0.37813	0.72698	0.64464
	2017	0.60695	0.42652	0.71922	0.64217
	2018	0.63513	0.4661	0.79013	0.64152
	2019	0.59976	0.52123	0.83199	0.65656

water resources and per capita water consumption remain high, resulting in the development level of the water resources subsystem in Shanghai for Zhejiang and Anhui.

The development levels of energy subsystem in all the regions are rising from 2013 to 2019. From the perspective of spatial distribution, although the total energy production in Shanghai is low in the Yangtze River Delta, the total energy consumption is relatively low. At the same time, the energy consumption per 10,000 yuan GDP is significantly lower than that in other regions, so the energy development level of Shanghai is higher than that of Jiangsu, Anhui, and Zhejiang.

The development level of the food subsystem in Shanghai is far lower than that in Jiangsu, Zhejiang, and Anhui. The total agricultural output value of Shanghai is very low, and the proportion of agriculture in the total national economic output value is very low, which can be almost ignored. Shanghai's grain mainly depends on the supply of other external provinces and cities, so the development level is very low. And there is a downward trend, which means that there are certain hidden dangers in Shanghai's food security. Local government departments need to strengthen food reserves to prevent food security problems.

The development level of the ecology subsystem in the whole Yangtze River Delta is on the rise. In particular, the level of ecological subsystem development in Jiangsu has been significantly improved. Overall, the development level of the ecology subsystem in Shanghai is lower than that in other regions.

Figure 3 presents the trend chart of the CDL values of each subsystem in each region as time varies. The phenomenon showed by these figures are consistent with our above discussion.

3.2. Coupling coordination development level

Based on the comprehensive development levels for each subsystem of WEFE obtained in last subsection, we calculate the coupling coordination degree for all the regions according to the model presented in Section 2.3.2. The results are listed in Table 4.

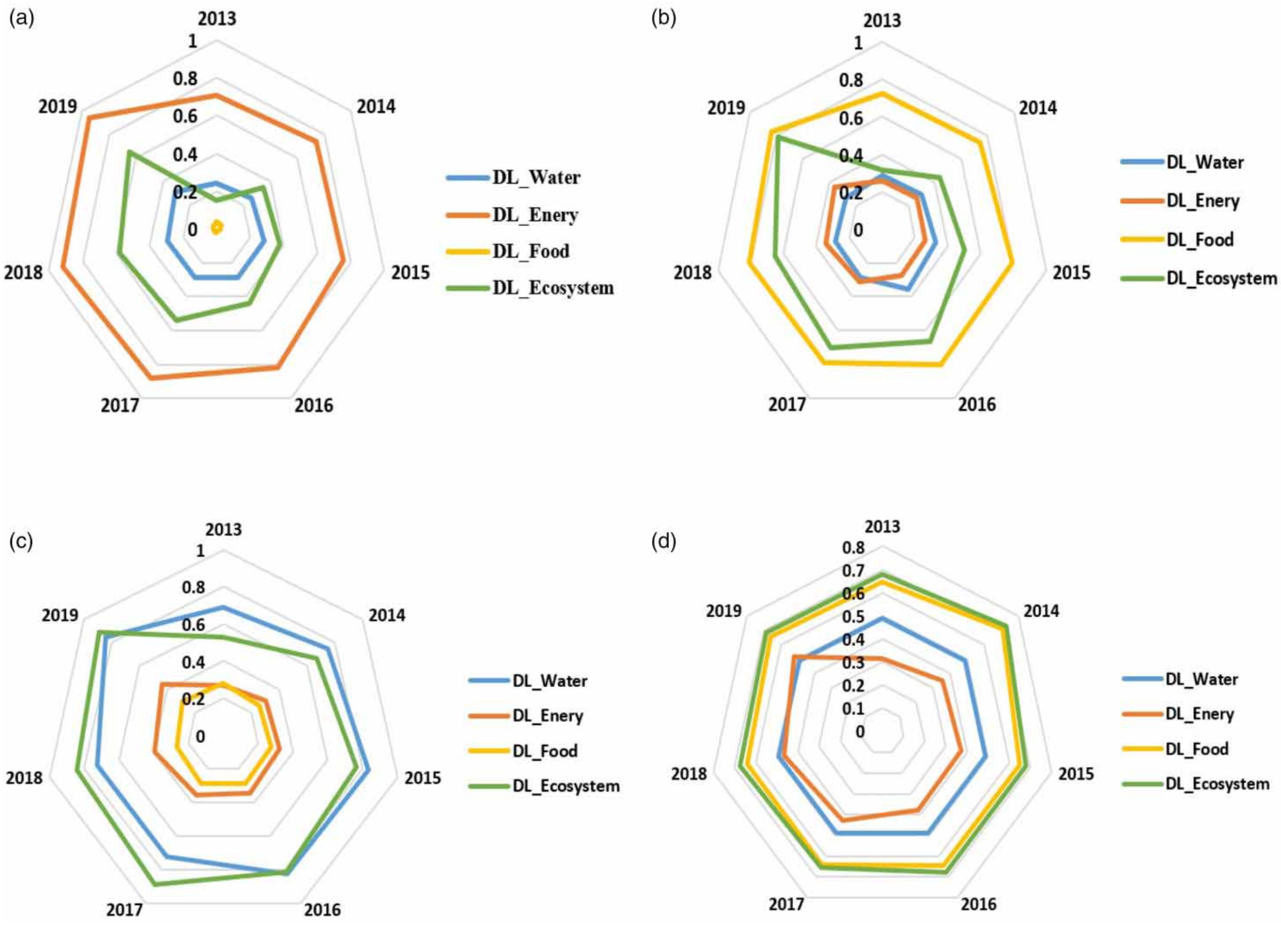

Figure 3 | Time variation trend of CDL of all the regions: (a) Shanghai, (b) Jiangsu, (c) Zhejiang (d) Anhui.

Table 4 | Coupling coordination development level in Yangtze River Delta

Region	Year	DCC	Region	Year	DCC
Shanghai	2013	0.422056596	Zhejiang	2013	0.637973005
	2014	0.467962103		2014	0.66676359
	2015	0.454735739		2015	0.699180778
	2016	0.442467424		2016	0.711670372
	2017	0.47686487		2017	0.711631027
	2018	0.493626127		2018	0.70940527
	2019	0.505922915		2019	0.746046478
Jiangsu	2013	0.600406834	Anhui	2013	0.712047384
	2014	0.632793032		2014	0.74443288
	2015	0.657000979		2015	0.751262375
	2016	0.692654391		2016	0.769993636
	2017	0.68844271		2017	0.766833628
	2018	0.690154609		2018	0.78891596
	2019	0.710544804		2019	0.79000000

As is shown in Table 4, the DCC level of Shanghai lies in near imbalance from 2013 to 2018, but its DCC value is increasing annually and the DCC level reaches barely coupling coordination in 2019. The DCC level of Jiangsu lies in primary coupling coordination from 2013 to 2018 and reaches intermediate coupling coordination in 2019. The DCC level of Zhejiang lies in primary coupling coordination in 2013 and 2014 and lies in intermediate coupling coordination after 2015, moreover, the DCC value is increasing gradually each year. The DCC level of Anhui lies always in intermediate coupling coordination. Anhui is abundant in water resources and energy. Meanwhile, it is one of the main grain production areas. In recent years, Anhui has been committed to improving the ecological environment, so the degree of coupling and coordination has gradually increased. All the evolutions of the DCC values for each region are presented in Figure 4.

As is shown in Figure 4, the DCC of Anhui is higher than other regions while of DCC of Shanghai is lower than other regions. The water resource, food, and energy are in serious shortage in Shanghai. Especially, the energy and food mainly depend on the supply or import from other regions. With the rapid growth of urbanization and economic development, the resource shortage problem will more serious, especially in the face of major disasters (Wang *et al.* 2021). In particular, the CDL of the food subsystem is very low and has a downward trend, which means there is a serious food security problem in Shanghai. The government needs to strengthen food reserves to prevent a food security problem. The results are consistent with the research of Li & Zhang (2020), in their research the development of subsystem and the whole system of the water-energy-food of Shanghai are much lower than there in Jiangsu, Zhejiang, and Anhui.

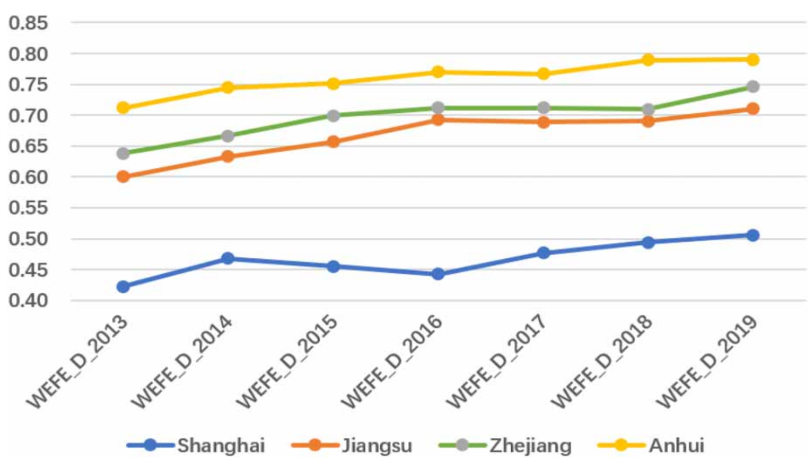

Figure 4 | The DCC levels of each region from 2013 to 2019.

4. CONCLUSION

In this study, we establish the evaluation index system of coupling coordination of water-energy-food-ecology (WEFE). Then based on the coupling coordination degree model and the projection pursuit model, the coupling coordination degree of WEFE in the Yangtze River Delta from 2013 to 2019 was calculated. The results show that the comprehensive evaluation of WEFE in the Yangtze River Delta is on the rising trend. Meanwhile, the coupling coordination degree of Anhui, Jiangsu, and Zhejiang is higher than that of Shanghai.

There are still many topics about WEFE coupling coordination, which is worthy of further research. For example, the improvement of the indicator systems and the important analysis of the indicators with the help of machine learning and other methods, so as to improve the evaluation of coupling coordination degree.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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