

Spatio-temporal analysis of human wellbeing and its coupling relationship with ecosystem services in Shandong province, China

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Abstract: Rapid economic and social change promotes to improve human wellbeing (HW), but poses threats to ecosystems and the environment. Studying the coupling relationship between HW and ecosystem services (ES) is crucial for informing high-quality development. Firstly, we built a comprehensive index system for HW assessment, and evaluated HW for 17 prefecture-level cities in Shandong province, China, from 2000 to 2018. Then, we quantified ES based on land use data. Finally, we assessed the coupling coordination degree and analyzed the relationships between HW and each type of ES value. The results were as follows: (1) HW values increased overall in Shandong, with the highest value in Jinan (0.8034) and the lowest value in Heze (0.4965) in 2018. (2) The total ES values for the 17 cities increased slightly. The ranking of 17 cities according to the ES value per unit area was different from the ranking according to the total ES value. (3) All 17 cities in Shandong were in the coordinated development phase after 2015, with increasing coupling coordination degrees. There were clear positive relationships between HW and ES. General and specific policy recommendations were proposed, providing scientific evidence and a reference for Shandong's urban management and policy formulation.

Keywords: land use; coupling; human wellbeing; ecosystem services; Shandong

1 Introduction

The rapid economic development around the world promotes constant improvements in residential living standards, with associated costs of natural resource consumption and envi-

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ronmental pollution (McDonough *et al.*, 2020; Wang *et al.*, 2021a). The declaration from The United Nations Millennium Ecosystem Assessment (EMA) has brought the relationships between human wellbeing (HW) and ecosystem services (ES) into the research sphere (Carpenter *et al.*, 2009; Yang *et al.*, 2013; Bottrill *et al.*, 2014). In China, the 14th Five-Year Plan (2021–2025) proposed that improving HW is one of six major goals for economic and social development from 2012–2025. In order to balance socio-economic development and natural protection, coordinated economic, social, and environmental development has attracted the attention of scholars and managers. Investigating the relationships between HW and ES can help achieve sustainable and coordinated development.

HW is used to evaluate the people's activities and states, considering basic material conditions, health, good infrastructure guarantee, safety, freedom of choice and action, etc. (MA, 2005). Scholars have focused on HW from the perspectives of concept presentation, phenomena description, evaluation, model simulation, and scenario prediction (Kates *et al.*, 2001). In general, HW can be divided into objective and subjective HW according to the research emphasis and subject (Huang *et al.*, 2016). Objective HW focuses on various conditions and facilities provided by society for a better life, such as tangible assets, income, education, etc. The most influential index is the Human Development Index (HDI) (Sagar and Najam, 1998). Loveridge *et al.* (2020) formulated a step-by-step Wellbeing Indicator Selection Protocol (WISP) considering economic and environmental indexes to analyze HW in Tanzania. Haq (2009) calculated HW for Pakistan's 100 administrative districts from 2006–2007 considering four conditions: education, health, living, and economy. In contrast, subjective HW considers an individual's cognition and the feeling of the surrounding social environment, involving happiness, life satisfaction, positive emotion, participation, personal ability, etc. (Fujita and Diener, 1997; McGillivray, 2007). Li *et al.* (2021a) investigated mental wellbeing through a survey, based on the adapted World Health Organization Well-Being Index. Zhang *et al.* (2021b) examined the effects of energy poverty on children's subjective wellbeing, using data from the China Family Panel Studies. Many other studies have been carried out, such as the wellbeing benefits of green and blue space (Fisher *et al.*, 2021). In summary, the previous literature focused on specific groups and priorities, and has not produced a public and unified index system for HW evaluation. More comprehensive indicators and aspects should be further explored.

ES refers to the various benefits that an ecosystem provides to human beings directly or indirectly through its structure, process, and function, which include provisioning, regulation, supporting, and cultural services (Costanza *et al.*, 1997; Jenkins *et al.*, 2010). In the 1960s, scholars began to evaluate ES. At present, ES evaluation methods are mainly divided into two categories, i.e., primary data based approaches and unit value based approaches (Xie *et al.*, 2017). Primary data based approaches include two steps: quantifying ecosystem processes and functions based on ecological models, followed by valuating ES using economic valuation techniques. The Integrated Valuation of Ecosystem Services and Tradeoffs (INVEST) model is often used to evaluate the value of a single ES and further analyze multiple ES, but cannot acquire the total value of all kinds of ES directly (Su and Fu, 2013; Yang *et al.*, 2019). The model requires many input parameters and contains complex calculation processes. As a representative unit value based approach, the equivalent factor method was developed by Xie *et al.* (2003), which can determine a single ES value through the material

or price value (Xie *et al.*, 2003; Costanza *et al.*, 2014) to analyze the overall pattern and change of ES in a region (Song and Deng, 2017; Jiang *et al.*, 2019). Such methods are the most widely used in China, especially for ES evaluation based on land use/cover change (LUCC).

Both the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the UK National Ecosystem Assessment (NEA) created conceptual frameworks to connect nature and people, linking human societies and their wellbeing with the environment (Díaz *et al.*, 2015) (NEA, 2011). Some related concepts such as nature's contributions to people and a good quality of life have been proposed (Díaz *et al.*, 2018). Natural ecosystems provide goods and services, such as benefits to people and a guarantee and pursuit of good quality of life. Living in harmony with nature has become an important topic for sustainable development and attracted the attention of various stakeholders, including residents, enterprises, institutions, and governments (Liu *et al.*, 2020). There are close and complex relationships between HW and ES (Figure 1). On the one hand, ES provide basic materials for social-economic systems and residential livelihoods, and form the foundation for sustainable development, which constrain HW. On the other hand, HW is driven by residential demands and preferences, and results in ecosystem decisions and transformation, which promote the changes of ES. At present, a series of studies have been carried out, with different conclusions. Guangshuo and Baohua (2012) found that there were no linear relationships between HW and ES in grasslands in Inner Mongolia and HW did not increase continuously. Other studies discussed the relationships between ES and HW at the national scale and found that there was a significant positive correlation between per capita ES and life satisfaction, but opposite relationships existed in some specific time series (Vemuri and Costanza, 2006; Engelbrecht, 2009). The reason may be attributed to the lag effects of the mutual feedback mechanism or the complex influences inside and outside the systems. In addition, scholars have found that study area and research scale are extremely important when analyzing the relationships between HW and ES. Wang *et al.* (2014) and Zhang *et al.* (2017) discussed the relationships between HW and ES in the upper reaches of the Miyun Reservoir at the township scale, as well as the upper reaches of Minjiang River at county scale, and put forward management strategies according to respective local conditions. Therefore, it is of great significance to study the relationships between HW and ES for coordinated management in a specific study area.

However, prior research still has the following shortcomings: (1) It is both difficult and important to reflect living conditions in a comprehensive, relevant way. The existing research on HW typically uses different evaluation index systems, which are largely influenced by the subjective factors of researchers. An index system for HW evaluation should be established based on current regional conditions and development goals. (2) Research on the relationships between HW and ES should be further investigated using quantitative evaluation methods. The separate relationships between HW and each type of ES should be further analyzed. Quantitative analysis models should be developed considering the research objectives and scale. Moreover, empirical studies in specific areas characterized by economic development, social change and other aspects, will contribute to policy formulation.

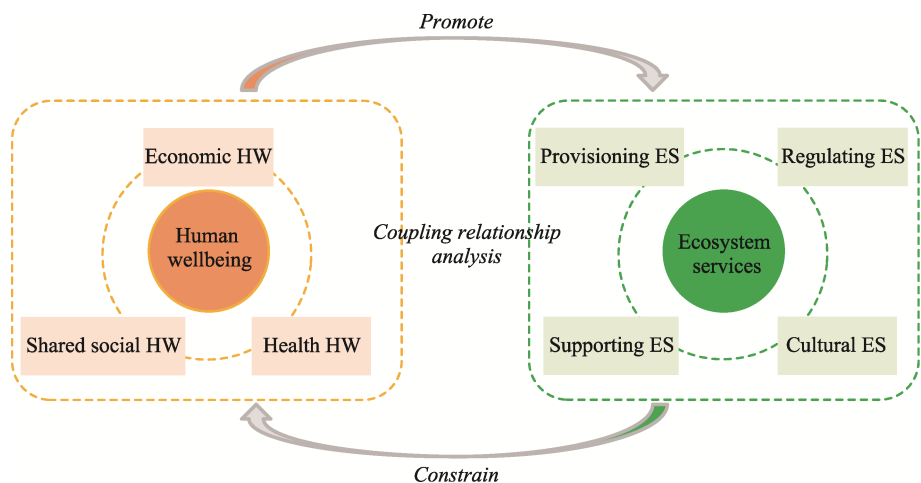


Figure 1 Coupling and coordination analysis between human wellbeing and ecosystem services

Shandong province, China, is undergoing rapid social improvement and pursuing high-quality development. Meanwhile, Shandong is in the important stage of new urbanization transformation and a transition to new economic engines. However, there also are evident gaps between the cities in terms of economic, social, and environment aspects (Chen and Yu, 2020). Residential quality of life in Shandong is uneven. It is important to investigate the spatio-temporal changes of HW in Shandong, especially at the prefecture-level city scale. Investigating the spatial and temporal changes in HW and ES can help to provide basic information for coordinated regional natural, social, and economic management. Moreover, it is urgent for Shandong to understand the coupling and coordination relationships between HW and ES to inform policy formulation and support regional sustainable and high-quality development.

Based on the literature review and research background, we first built a comprehensive index system for HW evaluation from economic, shared social, and health aspects, and assessed HW for 17 prefecture-level cities in Shandong from 2000 to 2018. Then, we quantified and analyzed the temporal and spatial characteristics of ES based on LUCC in Shandong in 2000, 2005, 2010, 2015, and 2018. Finally, we calculated the coupling coordination degree (CCD) between HW and ES and explored their relationships, which will support scientific policy recommendations for coordination and high-quality development.

The remaining sections of this paper are organized as follows. Section 2 describes the situation in Shandong and the sources of study materials. Section 3 illustrates the main methods. Results, discussion, and conclusions are provided in Sections 4, 5, and 6, respectively.

2 Study area and materials

2.1 Study area

Shandong province is located along the coast of eastern China near the lower reaches of the Yellow River, between 115°53′–119°05′E and 2°10′–1°50′N (Figure 1). In 2018 it had 17 prefecture-level cities under its jurisdiction. The cities in the Shandong make up the Shan-

dong Peninsula City Group. The region has a warm temperate monsoon climate, where the annual average temperature decreases from southwest to northeast and the average temperature is around 13°C. Precipitation is higher in the south and lower in the north, with an annual average annual of 600–750 mm. In 2018, the gross domestic product (GDP) was 6.6648×10^{12} yuan (the growth rate was 5.77% from 2017 to 2018), accounting for 6.77% of the total national GDP. Shandong’s permanent resident population exceeded 100 million at the end of 2017, and reached up to 100.47 million in 2018. The population urbanization level has experienced dramatic growth from 18.58% in 1990, to 26.78% in 2000, to 51.19% in 2018. Residential living standards and social welfare conditions have also greatly improved (Gao *et al.*, 2019). However, rapid development has come with the costs of resource consumption, environment pollution, and ecological degradation, placing tremendous pressures on sustainable development (Fan *et al.*, 2020). Moreover, from the perspective of socio-economic structure and natural resource distribution, Shandong is a microcosm of China (Zhang *et al.*, 2021a). Taking Shandong as the case study to explore HW and its relationship with ES can be representative of all of China and other similar regions.

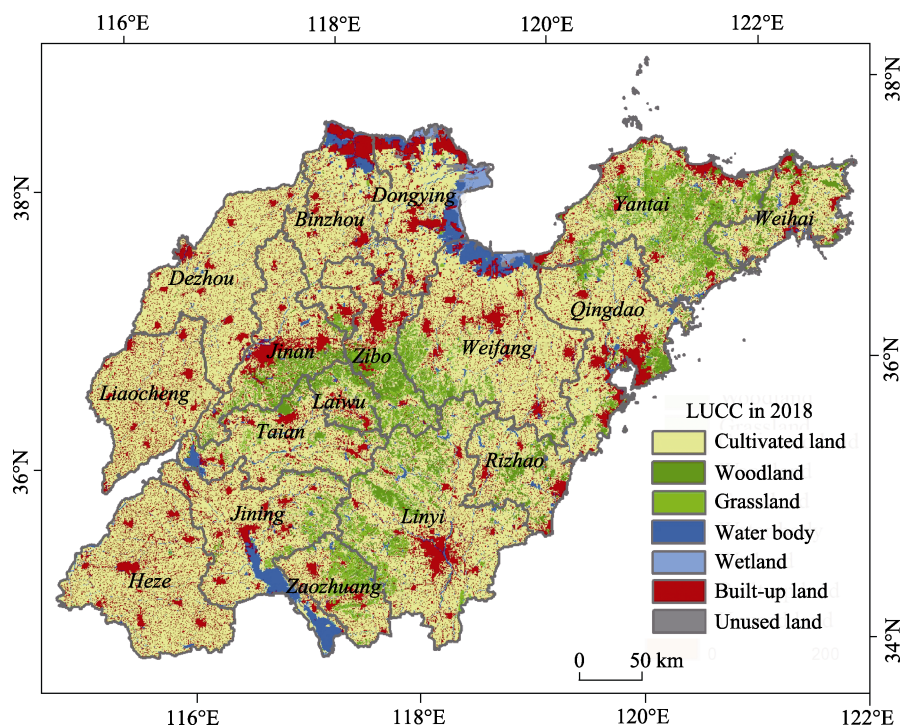


Figure 2 Location and land use and cover change of Shandong province, China

2.2 Data sources

The data used in this study primarily included spatial remote sensing data and statistics. A LUCC dataset for 2000, 2005, 2010, 2015, and 2018 with a 30 m×30 m resolution was obtained from the Data Center for Resources and Environmental Sciences (<http://www.resdc.cn>). Yield data for main crops (wheat, corn, and soybean) and economic, shared social, and health HW indexes were obtained from the *Shandong Statistical Yearbook (2001-2019)*.

Although Laiwu was merged into Jinan in 2019, we used the 17 cities including Laiwu as our study objects, considering that the study period was from 2000 to 2018. Statistical data were collected at the prefecture-level city scale. Shandong province included 17 prefecture-level cities, i.e., Jinan, Qingdao, Zibo, Zaozhuang, Dongying, Yantai, Weifang, Jinan, Taian, Weihai, Rizhao, Laiwu, Linyi, Dezhou, Liaocheng, Binzhou, and Heze. In addition, all economic data were adjusted by the price indexes of 2000 to eliminate the influence of price factors.

3 Methods

3.1 Human wellbeing index and evaluation

The UK NEA proposed that HW includes economic, shared social, and health values. The Chinese government also proposed the “14th Five-Year Plan”, emphasizing the eight key aspects of HW, i.e., employment, income and GDP synchronization, income distribution, public services, education, social security, health systems, and an anti-poverty rate. The Plan further emphasized closing the urban-rural gap. The evaluation of HW was population-centered and included comprehensive aspects. In light of this, numerous scholars (Zhao *et al.*, 2017; Bai *et al.*, 2018; Liu *et al.*, 2021) characterized the urbanization process. Some scholars (Leviston *et al.*, 2018; Loveridge *et al.*, 2020; Ayompe *et al.*, 2021; Liu and Wu, 2021) also tried to build an index system for HW. We summarized the indexes according to the categories and topics. Considering this emphasis, we built a comprehensive index system, including three aspects: economic, shared social and health (Table 1).

We used an entropy-weight method to access comprehensive HW (Liu *et al.*, 2021). In order to eliminate the influences of dimension, magnitude, and positive and negative orientation, all data were standardized using the range method. x_{ij} is the original value of index j in city i , and h_{ij} is the standardized value on a scale from 0 to 1.

$$\text{Positive index: } h_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \quad (1)$$

$$\text{Negative index: } h_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)} \quad (2)$$

The entropy E_j of the index can be calculated as follows.

$$E_j = -\ln(n)^{-1} \sum_{i=1}^n p_{ij} \ln p_{ij} \quad (\lim_{p_{ij} \rightarrow 0} p_{ij} \ln p_{ij} = 0, \text{ when } p_{ij} = 0) \quad (3)$$

$$p_{ij} = \frac{y_{ij}}{\sum_{i=1}^n h_{ij}} \quad (4)$$

The entropy weight of each index W_j is defined.

$$W_j = \frac{1 - E_j}{k - \sum_{i=1}^k E_j} \quad (j = 1, 2, \dots, k) \quad (5)$$

The final value of HW can be calculated as follows.

$$HW_i = \sum_{j=1}^k W_j h_{ij} \quad (6)$$

Table 1 The index system for comprehensive human wellbeing

Categories	Topic	Specific indexes (Unit)	Weight	Orienta- tion	Label
Economic human wellbeing	GDP	GDP per capita (yuan)	0.025450	+	ECO1
	GDP	Proportion of GDP in the secondary industry (%)	0.020861	+	ECO2
	GDP	Proportion of GDP in the tertiary industry (%)	0.023252	+	ECO3
	Employment	Proportion of employees at the end of the year (%)	0.032266	+	ECO4
	Employment	Proportion of employees in the secondary industry (%)	0.027415	+	ECO5
	Employment	Proportion of employees in the tertiary industry (%)	0.026771	+	ECO6
	Employment	Proportion of urban registered unemployed persons (%)	0.028193	–	ECO7
	Income	Average employee salary (yuan/person)	0.032531	+	ECO8
	Income	Disposable income of rural residents per capita (yuan/person)	0.033097	+	ECO9
	Income	Disposable income of urban residents per capita (yuan/person)	0.033208	+	ECO10
Shared social human wellbeing	Living standard	Consumption level of rural residents (yuan/person)	0.024914	+	SHA1
	Living standard	Consumption level of urban residents (yuan/person)	0.030837	+	SHA2
	Public service	Expressway density (km/100 km ²)	0.025960	+	SHA3
	Public service	Highway density (km/100 km ²)	0.039185	+	SHA4
	Public service	Retirement insurance benefits per capita (yuan/person)	0.027546	+	SHA5
	Public service	Proportion of urban employees participating in basic endowment insurance (%)	0.024556	+	SHA6
	Public service	Proportion of people participating in medical insurance (%)	0.043708	+	SHA7
Health human wellbeing	Public service	Proportion of people participating in unemployment insurance (%)	0.028819	+	HEA1
	Public service	Proportion of people participating in work-related injury insurance (%)	0.033610	+	HEA2
	Public service	Proportion of people participating in maternity insurance (%)	0.030953	+	HEA3
	Education	Teacher-student ratio in ordinary colleges and universities	0.023461	+	HEA4
	Education	Number of ordinary colleges and universities (units/person)	0.026943	+	HEA5
	Education	Books in public libraries per 100 people (books)	0.027847	+	HEA6
	Education	Cultural relics and cultural business expenditure per capita (yuan/person)	0.021438	+	HEA7
	Education	Education expenditure per capita (yuan/person)	0.031722	+	HEA8
	Medical treatment	Number of doctors per 10,000 people (persons)	0.022421	+	HEA9
	Medical treatment	Number of hospital beds per 10,000 people (beds)	0.026832	+	HEA10
	Medical treatment	Number of registered nurses per 10,000 people (persons)	0.025121	+	HEA11
	Medical treatment	Medical and health expenditure per capita (yuan/person)	0.035228	+	HEA12
	Health system	Industrial wastewater discharge per unit of GDP (tons/10 thousand yuan)	0.024265	–	HEA13
	Health system	Industrial SO ₂ emissions per unit of GDP (tons/10 thousand yuan)	0.021925	–	HEA14
	Health system	Industrial smoke (dust) emissions per unit of GDP (tons/10 thousand yuan)	0.017622	–	HEA15
	Health system	Green coverage rate in built-up area (municipal district) (%)	0.017193	+	HEA16
	Health system	Comprehensive utilization rate of general industrial solid waste (%)	0.025838	+	HEA17
	Health system	Centralized treatment rate of sewage treatment plants (%)	0.036245	+	HEA18
	Health system	Harmless treatment rate of domestic garbage (%)	0.022767	+	HEA19

3.2 ES evaluation based on LUCC

ES equivalent weighting factors are the value coefficients assigned to various types of ES to determine their value measured in monetary form, which are widely used in theoretical assessments formulae (Costanza *et al.*, 2014). The MA and UK NEA recognize four ES categories: provisioning services, regulating services, supporting services, and cultural services (Jiang, 2017). The equivalent weight factors of ES per area were defined referring to Xie *et al.* (2008), as shown in Table 2. We quantified territorial ES and reclassified the land use types into six types. i.e., cultivated land, woodland, grassland, water body, wetland, and barren land. Top level ES included provisioning, regulating, supporting, and cultural services (Costanza *et al.*, 1997; Zhan *et al.*, 2019). Second level ES were food production, raw production, gas regulation, climate regulation, hydrological regulation, waste disposal, soil retention, biodiversity protection, and landscape aesthetics.

Table 2 Equivalent weight factor of ES per unit area

Top level ecosystem services	Second level ecosystem services	Cultivated land	Woodland	Grassland	Water body	Wetland	Barren land
Provisioning services	Food production	1	0.33	0.43	0.53	0.36	0.02
	Raw production	0.39	2.98	0.36	0.35	0.24	0.04
Regulating services	Gas regulation	0.72	4.32	1.5	0.51	2.41	0.06
	Climate regulation	0.97	4.07	1.56	2.06	13.55	0.13
	Hydrological regulation	0.77	4.09	1.52	18.77	13.44	0.07
	Waste disposal	1.39	1.72	1.32	14.85	14.4	0.26
Supporting services	Soil retention	1.47	4.02	2.24	0.41	1.99	0.17
	Biodiversity protection	1.02	4.51	1.87	3.43	3.69	0.4
Cultural services	Landscape aesthetics	0.17	2.08	0.87	4.44	4.69	0.24
Total		7.9	28.12	11.67	45.35	54.77	1.39

Grain production can be affected by technological developments and climatic change, such as farm machinery, temperature, and rainfall. We used grain production per unit area (kg/km^2) as the equivalent value of ecosystems, considering the impacts of technology and climate conditions. We assumed that the actual value of grain production was seven times that of natural conditions (Fu *et al.*, 2012). Moreover, it was logical to eliminate the impacts of specific prices in the current food market. We used the emergy of food production per unit area (seJ/km^2) instead of monetary units (Liu *et al.*, 2019). The following equations were used to calculate the ES value.

$$VES = \sum_{k=1}^m (A_k \times V_k) \quad (7)$$

$$V_k = \sum_{i=1}^n (EK_{ik} \times U) \quad (8)$$

$$U = \frac{1}{7} \times \frac{\sum_{j=1}^z (P_j \times Q_j)}{S} \quad (9)$$

where VES represents the total estimated value of ES (seJ); A_k represents the area of land use type k (km^2); V_k represents the value of ES per unit area of land use type k (seJ/km^2). EK_{ik}

represents the equivalent weight factor of ES i of land use type k ; U represents the emergy of food production per area (seJ/km^2). P_j represents the emergy of crop j (seJ/kg); Q_j represents the yield of crop j (kg); S represents the sown area of the three main crops (km^2); $1/7$ is the value of the actual grain yield was seven times the value of the grain production under natural environment. Three main crop types (wheat, corn, and soybean) were considered in the emergy analysis. The emergy value of grain production in cultivated land per unit area was calculated through the emergy of the three main crops, as shown in Table 3.

Table 3 Ecosystem service value of grain production in cultivated land per unit area in Shandong

Year		2000	2005	2010	2015	2018
Grain yield ($\times 10^5 \text{ kg}/\text{km}^2$)	Wheat	4.70	5.49	5.78	6.18	6.09
	Corn	5.61	6.35	6.54	6.46	6.63
	Soybean	2.28	2.73	2.46	2.54	2.82
Annual solar emergy ($\times 10^7 \text{ J}/\text{kg}$)	Wheat	1.33	1.33	1.33	1.33	1.33
	Corn	1.45	1.45	1.45	1.45	1.45
	Soybean	2.07	2.07	2.07	2.07	2.07
Emergy transformity ($\times 10^4 \text{ seJ}/\text{J}$)	Wheat	6.80	6.80	6.80	6.80	6.80
	Corn	8.52	8.52	8.52	8.52	8.52
	Soybean	8.30	8.30	8.30	8.30	8.30
Proportion of grain acreage (%)	Wheat	56.30	52.47	53.37	53.44	49.82
	Corn	37.19	43.71	44.28	44.63	48.30
	Soybean	6.51	3.82	2.35	1.93	1.88
Total emergy of grain production per area ($\times 10^{17} \text{ seJ}/\text{km}^2$)		5.22	6.22	6.47	6.63	6.79

3.3 CCD estimation and analysis

The CCD model can characterize the development trend of a system or indicators from disorder to order. We used CCD to describe the relationships between HW and ES, and reflect the overall efficacy and synergies between them (Sun *and* Cui, 2018). According to Gan *et al.* (2020) and Liu *et al.* (2021), CCD can be calculated as follows.

$$D = (C \times T)^{\frac{1}{2}} \tag{10}$$

$$C = \left[\frac{HW \times ES}{\left(\frac{HW + ES}{2} \right)^2} \right]^{\frac{1}{2}} \tag{11}$$

$$T = \alpha HW + \beta ES (\alpha + \beta = 1) \tag{12}$$

where D is the CCD between HW and ES; C is the coupling degree, and T is the comprehensive evaluation index. D and C range from 0 to 1. T represents the over effects of HW and ES, with α and β representing the respective contributions of HW and ES to D . Furthermore, we used $\alpha = \beta = 0.5$ in the analysis. The CCD between HW and ES was divided into three categories in the first class and four categories in the sub-class for further evaluation, as shown in Table 4 (He *et al.*, 2017; Li *et al.*, 2021b).

Table 4 Classification of coupling coordination degree between HW and ES

Class	Sub-class	D-value
Coordination development (acceptable interval)	Superior balanced development	[0.7, 1]
Transitional development (transitional interval)	Slightly balanced development	[0.5, 0.7)
Unbalanced development (unacceptable interval)	Slightly unbalanced development	[0.3, 0.5)
	Severely unbalanced development	[0, 0.3)

4 Results

4.1 Spatio-temporal analysis of HW

All HW values for the 17 cities increased over time, as shown in Figures 3 and 4. In 2018, the HW value for Jinan (0.8034) was the highest of all the cities, followed by Qingdao (0.7980) and Zibo (0.6831). Heze (0.4965), Liaocheng (0.5023), and Linyi (0.5052) had the lowest HW. From the spatial dimension and prefecture-level city scale, HW values in the north were higher than in the south. Two growth nodes formed in the high HW value areas of “Jinan–Dongying” and “Qingdao–Weihai”. From 2000 to 2018, the three cities with the highest annual HW growth rates were Heze (13.17%), Zibo (9.91%), and Rizhao (9.84%). and the cities with the three lowest annual growth rates were Binzhou (7.12%), Weifang (7.62%), and Jinan (8.00%). With respect to the rankings of the three aspects, health HW > economic HW > shared social HW in 2000, compared to shared social HW > economic HW > health HW in 2018. The contribution changes demonstrated the following in the process of HW improvement: shared social HW took the lead, with the highest contributions to total HW in 2018, followed by economic HW, and health HW. In other words, shared social HW played a leading role in HW improvements, while the contributions of economic and health HW remained slight but relatively stable.

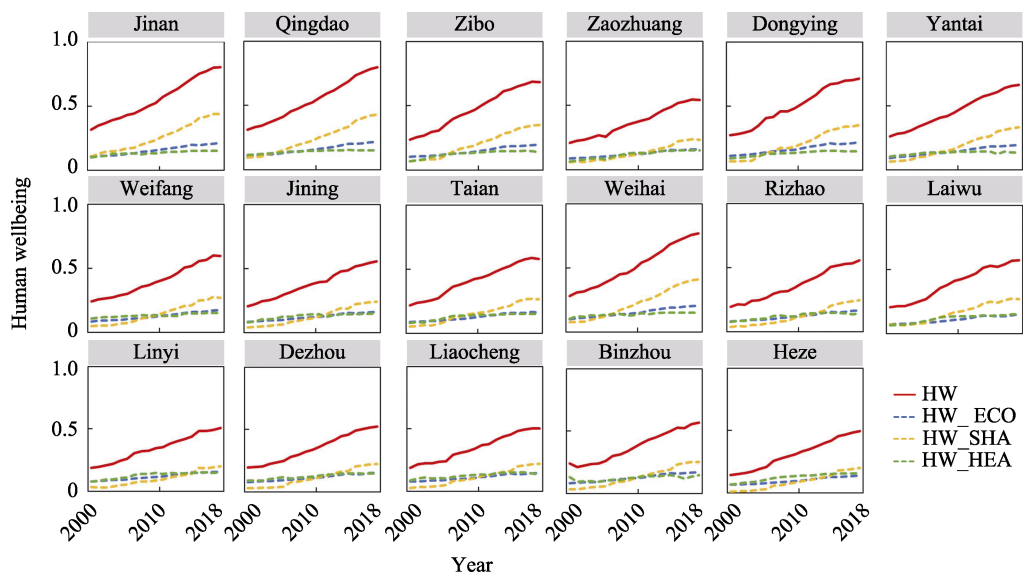


Figure 3 Changes in HW for the 17 cities of Shandong from 2000 to 2018. HW_ECO, HW_SHA, and HW_HEA represent economic, shared social, and health HW, respectively.

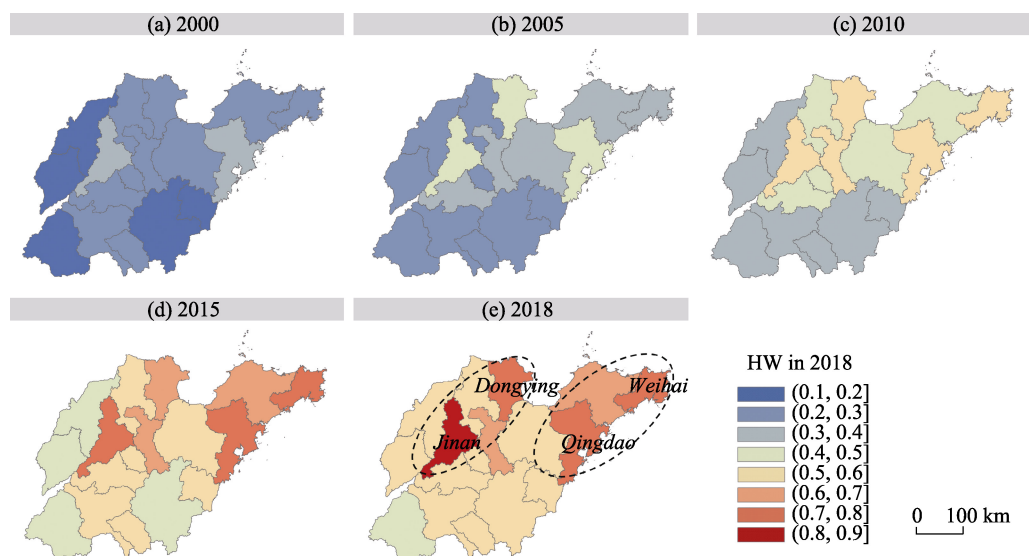


Figure 4 Spatio-temporal changes in ES value in the 17 cities of Shandong from 2000 to 2018

4.2 Analysis of LUCC and ES

Table 5 shows the ES values per unit area, LUCC, and ES values in Shandong in 2000, 2005, 2010, 2015, and 2018. Wetlands had the highest ES values per area, followed by water bodies, woodlands, and grasslands. Except for built-up land, ES value per area increased by 29.94% from 2000 to 2018. Cultivated land was the main land use type in Shandong, with a proportion of 63.90% in 2018. Built-up land had the second largest area of all the land use types, with a proportion of 19.07% in 2018. From 2000 to 2018, water bodies and built-up land expanded by 47.79% and 76.49%, whereas the areas of barren land, wetland, grassland, woodland, and cultivated land contracted by 73.37%, 41.36%, 38.03%, 8.96%, and 3.76%, respectively. The total ES value increased by 27.92% from 2000 to 2018. Cultivated land increased overall and had the highest proportion of the total ES value (52.57% in 2018). Water bodies and woodlands promoted increased ES in Shandong; their respective ES values increased from 11.85% in 2000 to 21.24% in 2018, and from 17.89% in 2000 to 16.55% in 2018. Otherwise, grassland, wetland, and barren land caused ES to decrease, with respective ES losses of 6.53%, 4.32%, and 0.06%.

The total ES values and ES per area for the 17 prefecture-level cities were summarized (Figure 5). Total ES values increased in varying degrees from 2000 to 2018. In 2018, Weifang, Linyi, and Yantai had the highest ES values, while Laiwu, Zaozhuang, and Rizhao had the lowest. Moreover, the values of provisioning services, regulating services, supporting services, and cultural services increased for all cities in Shandong. Regulating services contributed the most to total ES. In particular, Weifang (3.31×10^{22} seJ), Dongying (2.58×10^{22} seJ), and Linyi (2.03×10^{22} seJ) had higher growth ranges from 2000 to 2018. Because area and land use structure was different, the distribution of the ES per unit area among the 17 cities differed from ES. The ES value per unit area increased from 2000 to 2018. Dongying had the highest ES value per unit area in 2018, followed by Laiwu and Jining. In contrast, Liaocheng, Dezhou, and Heze had lower ES values per unit area.

Table 5 The area and ES values for each land use type in Shandong from 2000 to 2018

Year		2000	2005	2010	2015	2018
ES value per unit area (seJ/900m ²)	Built-up land	0	0	0	0	0
	Cultivated land (×10 ¹⁵)	3.7145	4.4195	4.5968	4.7153	4.8269
	Woodland (×10 ¹⁶)	1.3222	1.5731	1.6362	1.6784	1.7181
	Grassland (×10 ¹⁵)	5.4871	6.5285	6.7905	6.9655	7.1303
	Water body (×10 ¹⁶)	2.1323	2.5370	2.6388	2.7068	2.7709
	Wetland (×10 ¹⁶)	2.5752	3.0640	3.1869	3.2691	3.3464
	Barren land (×10 ¹⁴)	6.5356	7.7760	8.0881	8.2965	8.4928
Area (× 900 m ²)	Built-up land (×10 ⁷)	2.2412	2.4441	3.0018	3.1277	3.3123
	Cultivated land (×10 ⁸)	1.1530	1.1427	1.1429	1.1297	1.1097
	Woodland (×10 ⁷)	1.1024	1.1028	1.0023	1.0023	1.0036
	Grassland (×10 ⁷)	1.5408	1.4655	0.94489	0.9449	0.9549
	Water body (×10 ⁶)	4.5255	5.2840	7.1694	7.2842	7.9869
	Wetland (×10 ⁶)	2.2470	1.8295	1.8326	1.7310	1.3175
	Barren land (×10 ⁶)	2.5479	1.9594	7.5377	7.4714	6.7977
	Total (×10 ⁸)	1.7347	1.7347	1.7354	1.7348	1.7366
ES value (seJ)	Built-up land	0	0	0	0	0
	Cultivated land (×10 ²³)	4.2828	5.0503	5.2537	5.3267	5.3562
	Woodland (×10 ²³)	1.4576	1.7349	1.6400	1.6823	1.7242
	Grassland (×10 ²²)	8.4546	9.5674	6.4163	6.5815	6.8084
	Water body (×10 ²³)	0.9650	1.3405	1.8919	1.9717	2.2131
	Wetland (×10 ²²)	5.7866	5.6056	5.8404	5.6586	4.4088
	Barren land (×10 ²¹)	1.6652	1.5237	0.6097	0.6199	0.5773
	Total (×10 ²⁴)	0.8146	0.9658	1.0017	1.0211	1.0421

4.3 Coupling coordination analysis between HW and ES

Figures 6a–6e show the CCD between HW and total ES (CCD1), provisioning services (CCD2), regulating services (CCD3), supporting services (CCD4), and cultural services (CCD5), respectively. All five CDD values in the 17 cities increased from 2000 to 2018. Average CCD1 (Figure 6a) increased from 0.6365 in 2000 to 0.8652 in 2018, with an average annual growth rate of 1.89%. Dongying (0.9717, maximum), Weihai (0.9535) and Jinan (0.9181) had the highest CCD1 values in 2018, while Dezhou (0.7725), Heze (0.7653) and Liaocheng (0.7474, minimum) had the lowest. According to the classification (Table 4), there were 16 cities in a transitional development phase in 2000, while only one (Jinan, 0.7014) was in a coordination development phase. Compared to 2000, all 17 cities were in a coordinated development phase in 2015 and 2018, which showed that Shandong were in superior balanced development across the whole region at the prefecture-level city scale. Comparing the four CCDs (Figures 6b–6e), CCD2 and CCD4 were higher than CCD 3 and CCD5. The average values of CCD2-5 were 0.6627, 0.5984, 0.6464, and 0.5815 in 2000, respectively, while 0.8924, 0.8194, 0.8657, and 0.7980 in 2018, respectively. In 2018, CCD

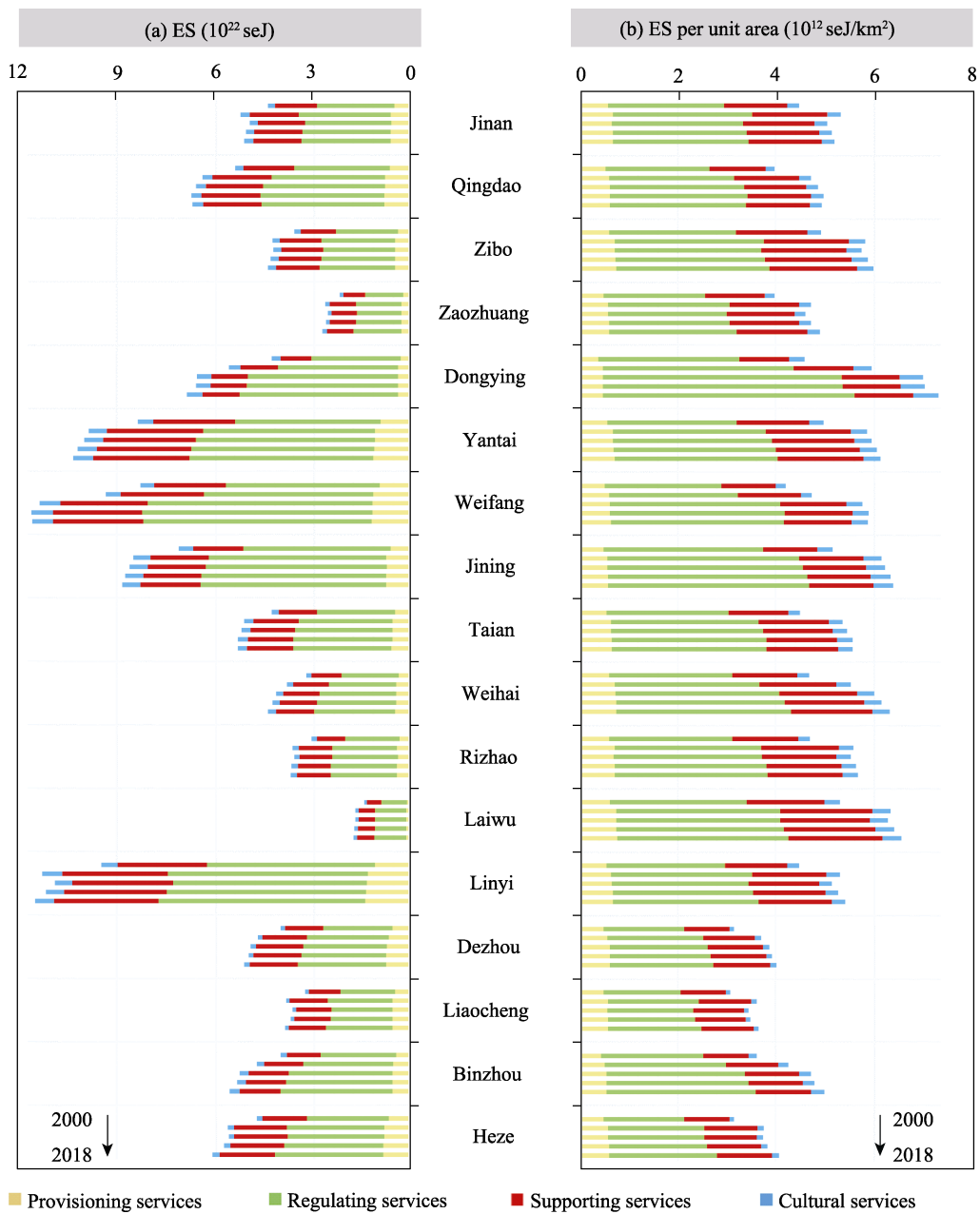


Figure 5 ES and ES per area values for the 17 cities in Shandong from 2000 to 2018

2 and CCD 4 values were in the superior balanced development category (>0.7) in all of Shandong. CCD 3 values for 16 cities (except for Liaocheng, which was in a slightly balanced development phase) reflected superior balanced development; and CCD 5 values for 14 cities (except for Dezhou, Liaocheng, and Heze that were in a slightly balanced development phase) reflected superior balanced development. Based on the results, we found that HW achieved coordinated development with provisioning and supporting ES. Regulation and cultural ES should be further improved, especially in Dezhou, Liaocheng, and Heze.

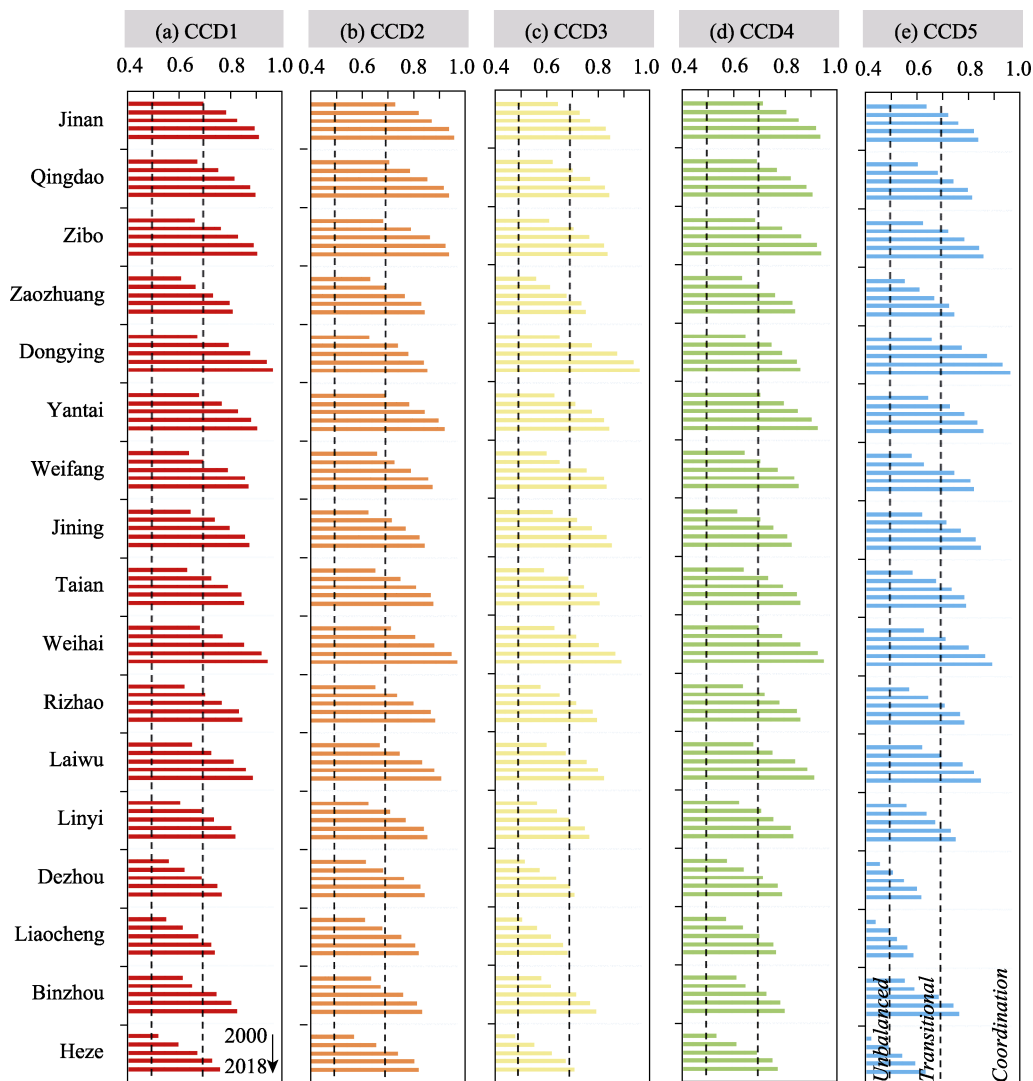


Figure 6 Coupling degree between HW and ES from 2000 to 2018 in Shandong. CCD1, CCD2, CCD3, CCD4, and CCD5 present the CCD between HW and total ES, provisioning services, regulating services, supporting services and cultural services, respectively.

In order to illustrate the detailed relationship between HW and ES, we generated scatter diagrams between the standardized values of HW and ES per unit area. As shown in Figure 7, there were evident positive linear relationships between HW and ES per unit area, and both increased from 2000 to 2018. The coefficient between HW and total ES per unit area was 0.3303 ($R^2=0.2647$). By comparing the four liner relationships in Figures 7b-7e, coefficients between HW and regulating ES per unit area (0.3138) and cultural ES per unit area (0.3687) were high, whereas coefficients between HW and provisioning ES per unit area (0.2265) and supporting ES per unit area (0.2337) were low. The span of regulating and cultural ES per unit area was larger than other two ES per unit area, indicating that there were bigger gaps in regulating and cultural ES supply capacity among the prefecture-level cities. Therefore, improving cities with low ES supply capacity would help achieve coordinated and sustainable development.

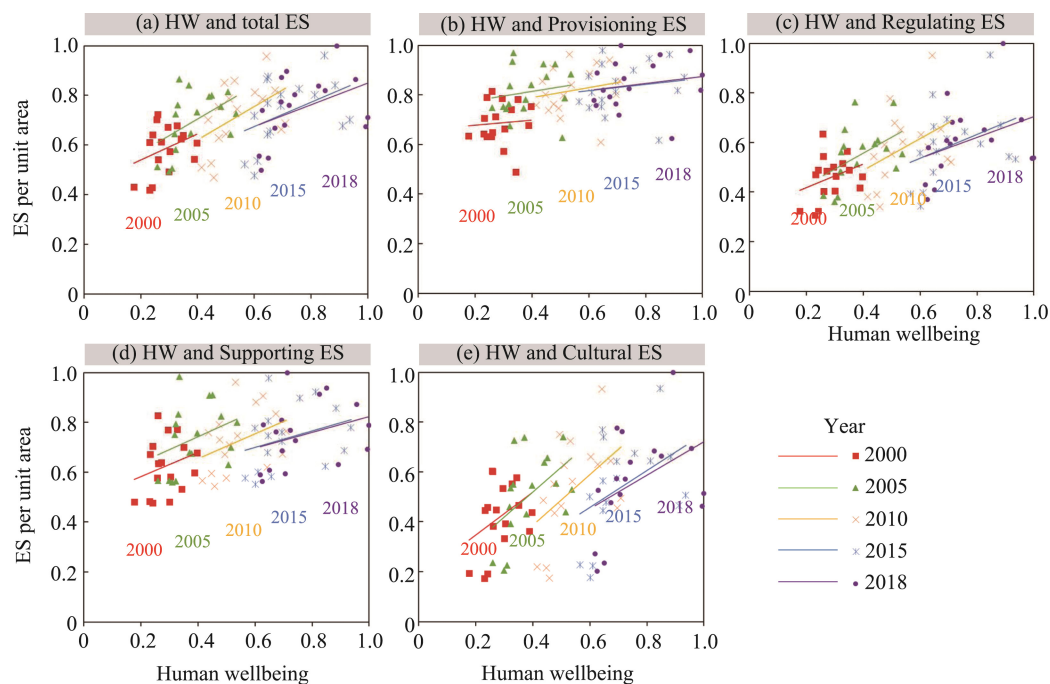


Figure 7 The relationships between HW and ES per unit area

5 Discussion

5.1 Dynamic changes in LUCC, ES, and HW

LUCC, ES, and HW reflect complex and dynamic systems. There are many factors inside and outside these systems that influence the main indicators. These factors also interact with each other (Wang *et al.*, 2017). The results and analysis could exhibit some tiny differences depending on the focus.

The land use patterns and LUCC in Shandong consistent with previous studies (Deng and Gibson, 2019; Jin *et al.*, 2019). Shandong is a major grain producer in China. Cultivated land is the main land use type, with a proportion of more than 60% of the total land area (Deng *et al.*, 2017). In the ES assessment method of Xie *et al.* (2008) cultivated land yield production was taken as the equivalent, and it was reasonable to adopt the method in this study. Land urbanization was evident, especially around the central urban area. Costly built-up land would contribute to a decrease in ES and landscape fragmentation. The amount of water body and wetland coverage increased somewhat, leading to an increase in ES.

Moreover, there were different rankings between the ES and ES per area of the 17 cities. The total ES was mainly determined by administrative area. Large cities, such as Linyi, Weifang, and Yantai, had higher total ES. However, ES per area represents the ES supply capacity, which is mainly contributed by non-built-up areas. Cities with large woodland, grassland, water body and wetland areas had higher ES per area. For example, Donying and Jining had higher ES per area due to the large proportion of water body and wetland cover; Laiwu had higher ES per area due to the large woodland and grassland cover. Heze, Liaocheng and Dezhou, located in west Shandong, had low ES per area values.

The HW index system used in this study synthesized the conceptual framework from MA and IPBES. Some specific indicators were added after considering the typical study area. Economic development and social change should improve residents' living standards, living environment, and other aspects (Zhang and Bai, 2018; Wang *et al.*, 2021b). The increase in HW from 2000 to 2018 was consistent with the actual situation. A comparative analysis of sub-HWs would improve HW. The index results showed that shared social HW contributed most to the increase in HW from 2000 to 2018. Therefore, economic and health HW should be further explored to improve total HW.

ES was an important contributor or component of HW. The complex relationship is not a one-to-one correspondence, and many factors affect each other (Pröbstl-Haider, 2015). In fact, the earliest study developed methods and models to explore the relationship between two variables. The environmental Kuznets curve (EKC) was developed to analyze pollution and environmental capacity with the urbanization process. The STIRPAT model (York *et al.*, 2003) was used to study environmental influencing factors. Multi-agent models (Bijandi *et al.*, 2021) were built to simulate and optimize dynamic land and water management systems. Big data and urban computing models (Ma *et al.*, 2020) were used to discover the mechanisms hidden in big data. However, the above methods and models focused on the impacts of one variable on the other variables, neglecting the corresponding feedback relationships. The coupling model emphasizes the interactions between two systems or indicators (Liu *et al.*, 2021). Therefore, coupling and coordination analysis was adopted as the best way to explore the relationships between HW and ES (Xu *et al.*, 2019). The relationship is not completely represented by a single index or a linear relationship. Moreover, different α and β values could be analyzed for CCD, such as $\alpha=1/3$ and $\beta=2/3$, or $\alpha=2/3$ and $\beta=1/3$. Our mainly objective was to track the changes trends and trajectories of CCD, so we set $\alpha=\beta=0.5$. However, the results were consistent with the facts and revealed the relationships, contributing to policy formulation and practical applications.

5.2 Policy implications

(1) General recommendations to improve coupling coordinated development

CDD increased from 2000 to 2018 and was greater than 0.7 in 2018. However, considering the gaps and variations of HW and ES among the cities, local governments and relevant departments should still focus on coupling coordinated development. There are two main policy implications. (1) Continue to improve ES and HW and increase CCD. All cities should strengthen regulating and cultural ES, considering the synergy and trade-off among the four ES types. They should promote the new-type urbanization transformation and development new drivers to boost economic growth and improve wellbeing. (2) Manage and pursue balanced development across all of Shandong. The government should pay more attention to the relatively backward areas, such as Dezhou, Liaocheng, and Heze with low HW, ES, and CCD. More specific policies should be formulated to eliminate the gaps between urban and rural areas and different cities.

(2) Specific recommendations based on the relationships between HW and ES

In order to propose specific policy recommendations, we divided the 17 cities according to their HW and ES relationships, as shown in Figure 8. We used the mean values of HW and ES as the demarcation lines to define the four categories, i.e., High HW and High ES

(HH), High HW and Low ES (HL), Low HW and High ES (LH), and Low HW and Low ES (LL). Based on the CDD, we proposed specific policy suggestions for the urban categories. (1) For category HH (Weihai, Yantai, and other cities in the upper right quadrant in Figures 8a–8e): maintain HW and ES supply capacity, keep and increase coordinated development between HW and ES, improve conditions across all aspects, pursue high-quality and sustainable development. (2) For category HL (Qingdao and other cities in the lower right quadrant in Figures 8a–8e): promote pollution control and ecological protection, increase the coverage of ecological land, avoid economic development at the expense of the environment, promote industrial transformation and transitions to new economic engines. (3) For category LH (Laiwu, Rizhao, Taian, and other cities in the upper left quadrant in Figures 8a–8e): develop tertiary industry and eco-tourism relying on natural ecological conditions, encourage eco-agriculture, increase ecological subsidies and poverty alleviation, and formulate stable regional development plans, including land use space planning, etc. (4) For category LL (Heze, Dezhou, Liaocheng, and other cities in the lower left quadrant in Figures 8a–8e): focus on eliminating the contradiction between human and nature, improve CDDs, seek pathways to protect the environment and improve people’s livelihoods and welfare at the same time, such as poverty alleviation, ecological compensation, and developing ecological agriculture.

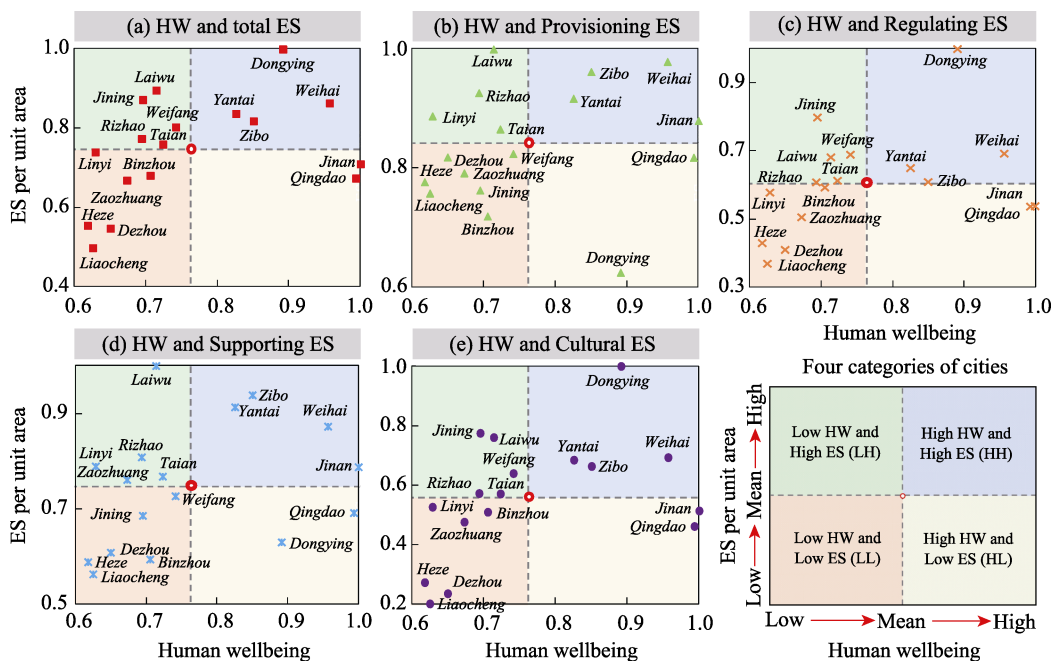


Figure 8 The categories of the 17 cities of Shandong province according to HW and ES in 2018

5.3 Limitations and perspectives

This study had some limitations in the framework and method: (1) We assessed ES based on LUCC and transferred it into values with emergy units. The equivalent weighting factors from related references were adopted in Shandong. There may have been some slight gaps in

the ES assessment. (2) The HW assessment focused on prefecture-level cities and used data mainly from local statistic books. The index system was limited by the statistics to a certain extent. The HW investigation and assessment could be further explored based on the current research. (3) We adopted a CCD model to represent the coupling degree and used linear regression to describe the relationships. The relationships were just a representation, not the real mechanism. These limitations cannot affect the credibility of the results and the significance of policy implications.

Based on the methods and results of this study, we propose the following future research ideas. (1) The values of the three sub-HWs are decided by the specific indicators and the weight. The results would be influenced by the weight method. Therefore, there are some uncertainties in the weight method. A more comprehensive index system and methods could be further explored in the future. Moreover, questionnaire surveys and more detailed research scales may yield more detailed conclusions. (2) ES is not a definition with clear boundaries. More types of ES could be incorporated into the assessment. For example, marine ES should be further investigated to development an ES management framework (Sun *et al.*, 2018). (3) The relationships between HW and ES or other aspects should be further explored using more valid simulation models. Scenario analysis also can be used for policy formulation and to support system optimization.

6 Conclusions

In order to explore the spatio-temporal changes in HW and the coupling coordination relationship with ES, we carried out a case study in 17 prefecture-level cities in Shandong, China. The results and conclusions can provide useful evidence to formulate policy for high-quality development.

We found the following conclusions. (1) HW values overall increased from 2000 to 2018, with two growth nodes in the clustered areas of “Jinan–Dongying” and “Qingdao–Weihai”. Meanwhile, among the three aspects, shared social HW had the biggest contribution to the increase of HW, followed by economic HW and health HW. (2) LUCC was stable from 2000 to 2018. Cultivated land was the dominant land use type. The total ES values and ES per unit area of the 17 cities increased from 2000 to 2018. The structure of ES per unit area among the 17 cities was different from the structure of ES. In 2018, Dongying, Laiwu, and Jining had the highest ES values per unit area, while Liaocheng, Dezhou, and Heze had the lowest. (3) CCDs in the 17 cities increased from 2000 to 2018. Shandong achieved superior balanced development across the whole region at the prefecture-level city scale by 2018. There were clear positive relationships between HW and ES. Coefficients between HW and regulating ES (0.3138) and cultural ES (0.3687) were relatively high. (4) Some general and specific policy recommendations were proposed based on the results of HW, ES, and CCD. Shandong should maintain the stable increasing trend of CCD, and pursue balanced development. Moreover, four categories were identified according to the relationships between HW and ES: HH, HL, LH, and LL. Specific recommendations were proposed for the cities in each category. (5) Although there were some calculation and analysis limitations in this study, they do not affect the application of the results and conclusions. In the future, more comprehensive index systems or assessment methods could be further explored. Scenario analysis for the relationships between HW and ES or other aspects should be explored. The-

se results and conclusions would contribute to regional spatial management and high-quality achievements for Shandong and other regions.

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