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Drivers of Regional Environmental Pollution Load and Zoning Control: A Case Study of the Yangtze River Economic Belt, China

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Abstract: The high environmental pollution load caused by the massive pollutant emissions and the accumulation of endogenous and cross-regional pollution has become an important obstacle to the current ecological civilization construction in the Yangtze River Economic Belt (YREB) in China. Taking the YREB as an example, by using four environmental pollutant emission indicators, including chemical oxygen demand (COD), ammonia nitrogen (NH_3-N), sulfur dioxide (SO_2), and nitrogen oxides (NO_x), this paper established an environmental pollution load index (EPLI) based on the entropy-based measurement. Moreover, the Spatial Durbin Model was used to quantitatively analyze the drivers and spatial effects of environmental pollution load. Finally, specific scientific references were provided for formulating environmental regulations of pollution source control in the YREB. The results showed that: 1) During 2011–2015, the EPLI in the YREB was reduced significantly and the environmental pollution load increased from upstream to downstream. Among them, the pollution load levels in the Upper Mainstream subbasin, Taihu Lake subbasin, and Lower Mainstream subbasin were the most prominent. 2) The environmental pollution load situation in the YREB was generally stable and partially improved. High load level areas were mainly concentrated in the Yangtze River Delta Region and the provincial borders in upstream, midstream, and downstream areas. The high load level areas already formed in Chengdu and Chongqing were also the key regulatory points in the future. 3) The degree of local environmental pollution load was apparently affected by the adjacent cities. The population size, industrialization level, and the fiscal decentralization not only drove the increase of the local environmental pollution load level, but also affected the adjacent areas through the spatial spillover effects. The land development intensity mainly drove the increase in the local EPLI in the YREB. While factors such as economic development level and agricultural economic share could only act on the environmental pollution load process in adjacent cities. 4) According to the differentiation characteristics of drivers of each city, the YREB was divided into seven zones based on *k*-medoids cluster method, and targeted zoning control policy recommendations for alleviating environmental pollution load in the YREB were proposed.

Keywords: environmental pollution load; drivers; spatial effects; Spatial Durbin Model; Yangtze River Economic Belt

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1 Introduction

Since there is limited capacity of regional environmental system to contain pollutants, pollutant discharges need to be controlled within the carrying capacity (Lazarus and Cohen, 1997, El Ouardighi et al., 2014).

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However, with the accelerated urbanization and industrialization and the rapid socioeconomic development, the high energy consumption, and high-density land expansion have led to a large amount of pollutant emissions, endogenous and cross-regional accumulation of pollution. Thus, the rapid increase in anthropogenic pollutant discharges from various production and living activities, such as industrial production, farming, urban and rural residential life, transportation, and other activities, will aggravate the process of regional environmental pollution load, resulting in structural imbalance, functional degradation, and even system collapse of the ecological environment (Clark, 1980). Therefore, reducing environmental pollution load has become a common concern for global sustainable development (European Commission (EC), 2010; United Nations (UN), 2015; National Development and Reform Commission (NDRC), 2016), researchers and environmental policy makers both hope to alleviate regional environmental pollution load, as well as achieving social and economic development (Epstein et al., 2011; Han et al., 2018). In China, the high-intensity environmental pollution load has threatened the sustainable development of regional population, resources, and environment (Lu et al., 2015; Gao et al., 2019), and has become the main obstacle to the construction of ecological civilization, especially in the Yangtze River Economic Belt (YREB) (Lu, 2018; Xia and Zuo, 2018). Against this background, since 2010, the Chinese government has established the basic principles of 'Ecology Priority and Green Development', and placed the protection and restoration of the Yangtze River at the forefront the YREB. Consequently, the pollution control and management of the whole basin had been gradually strengthened, and the overall goals of environmental improvement and pollution control scheme were formulated in the YREB. Therefore, in order to cope with the serious environmental pollution load faced by the YREB, by analyzing the spatio-temporal variation and main drivers of the environmental pollution load, the environmental regulation oriented to pollution source control can be formulated, and the comprehensive measures can be taken to guide the sustainable development of the population, economy, and environment.

In recent years, studies on the spatio-temporal variation of environmental pollution load have been appearing constantly. In the research of environmental pollution load represented by a single pollutant, by using spatial statistical analysis, air pollutants such as SO_2, and water pollutants such as COD and NH_3-N were found mainly concentrated in industrial areas, major mining areas, and urbanized areas (Li et al., 2014; Zhou et al., 2017; 2021). (Song et al. 2017) further found that the air pollution load presented a circle distribution pattern that gradually decreased from the urban agglomeration to the periphery through the PM2.5 data. Due to the spatio-temporal differences in the discharges of different pollutants, it is arduous to fully characterize the integrated pollution stress faced by the regional environment (Liu and Gao, 2019). Some studies then had gradually shifted from single pollutant to comprehensive integration, and the similar spatial agglomeration characteristics and spillover effects had been confirmed in these integrated studies. Guo et al. (2018) and Zou et al. (2005) analyzed the agglomeration of provincial environmental pollution load using the geographic concentration index, and Jia et al. (2020) also examined the spatial spillover effects of the environmental pollution load with an industrial pollution comprehensive index.

Empirical studies on drivers of environmental pollution load are a classic topic. Studies on the population and social factors mainly focused on the environmental impact of population, affluence, technology (IPAT) model, and their interrelationship, and found that population growth and material consumption are the main factors causing the increase in environmental pollution load (Ehrlich and Holdren, 1971; Parikh and Shukla, 1995). Subsequently, by relaxing the restrictions on the same proportional changes in various factors in the IPAT model, studies had further developed the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) model and confirmed that the increase in urban population would bring greater environmental pollution load (rease in urban population would bring greater environmental pollution load (Dietz and Rosa, 1997; Cole and Neumayer, 2004). Jones (1991) argued that this may be largely due to differences in transportation and energy structures between urban and rural areas. For the relationship between economic drivers and environmental pollution load, Walter and Ugelow (1979) suggested that the demand for economic growth in low-income countries would lead to a relaxation of environmental restrictions, triggering the concentration of polluting foreign capital and forming 'pollution paradise'. Later, Grossman and Krueger (1991) found an inverted U-shaped curve relationship between environmental pollution load and economic growth through long-term research, and put forward technological progress and advanced industrial structure as the main reasons for the decline in environmental load (Grossman and Krueger, 1995; Fong and Shibuya, 2020). Around this theme, many empirical studies had been carried out at the national and provincial levels (Baek, 2016; Sapkota and Bastola, 2017; Liu et al., 2018; Liu and Lin, 2019), and had confirmed the validity of the hypothesis on a large scale. Moreover, based on spatial econometric methods, subsequent research has progressively deepened the economic factors into industrial structure, technological progress, and other factors. Liu and Lin (2019) confirmed that technological progress can alleviate the degree of environmental pollution load. Liu et al. (2017) found that the urbanization and industrialization progress exacerbated the atmospheric environmental pollution load based on the spatial Durbin model. In addition, studies on policy factors such as fiscal decentralization and environmental regulation showed that strong environmental policies have two sides to environmental pollution load. Namely, while reducing the degree of local pollution stress, it would promote the spatial transfer of pollution sources across regions, resulting in intensified stress in adjacent areas (Tan and Zhang, 2015; Li et al., 2017; Zhu et al., 2018). In the empirical studies of the YREB, Zhou et al. (2018) further revealed that the impact of economic development level on environmental pollution load presents differences among watersheds. Ping et al. (2019) and Sun and Cheng (2019) also confirmed that the industrialization level has cumulative amplification and spatial spillover effects.

In the existing environmental pollution load research, single pollutants with significant pollution load to specific environments such as atmosphere and water body have been focused on, while the comprehensive evaluation of environmental pollution load should be strengthened. And although the characteristics of the socio-economic drivers of environmental pollution load are preliminarily analyzed in the empirical studies, the spatial effects of the regional environmental pollution loads caused by them are rarely discussed. From the perspective of research, there are currently many studies on cities and countries, but few studies explore the spatial differences in different regions from the perspective of drivers.

Therefore, taking 127 prefecture-level city units in the YREB as empirical cases, based on the entropy-based environmental pollution load index (EPLI) measurement, by using four pollutants of chemical oxygen demand (COD), ammonia nitrogen (NH_3-N), sulfur dioxide (SO_2) and nitrogen oxides (NO_x), which can indicate various production and living activities such as industrial production, farming, urban and rural residential lives, and transportation, this paper analyzed the spatio-temporal changes and spatial correlation characteristics of environmental pollution load in the YREB during the social and economic transition period from 2011 to 2015. Under the framework of the STIRPAT model, the optimal model among spatial lag model, spatial error model, and spatial Durbin model was selected to quantitatively decompose the drivers and spatial effects of environmental pollution load. The *k*-medoids clustering method was used to cluster statistics for areas with similar influencing factors, to provide references for the formulation of environmental joint prevention and control and emission reduction countermeasures for YREB, and enhance the source control ability of the whole basin.

2 Materials and Methods

2.1 Study area and data source

The YREB includes nine provinces and two municipalities in China (Fig. 1), of which the total area is about 2.05 million km^2, accounting for 21% of the national land area. The population and GDP of the YREB was 610 million and 37.56 trillion yuan (RMB) in 2015, accounting for 44.12% and 50.68% of China, respectively. In addition, the YREB accounted for 44.54% of national wastewater emissions and 35.70% of national waste gas emissions. In 2015, COD, NH_3-N, SO_2, and NO_x emissions in the YREB accounted for 36.48%, 43.42%, 34.15%, and 32.01% of the national total, respectively (National Bureau of Statistics of China, 2012–2016c).

In this study, a database of environmental pollutant emissions and socioeconomic development in the YREB from 2011 to 2015 was constructed, including two municipalities directly under the Central Government of Shanghai and Chongqing, and 125 other prefecture-level cities. Data on total emissions and the sources

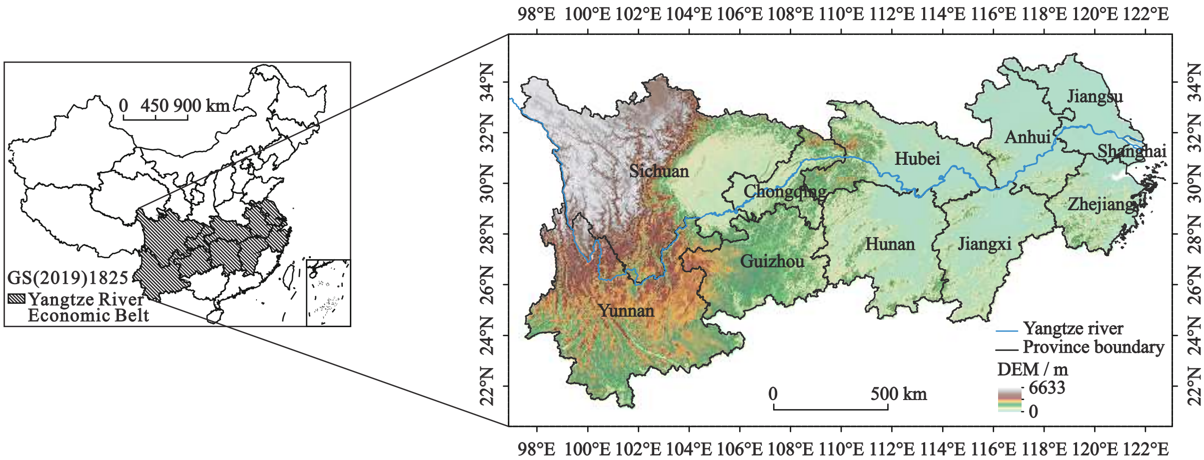

Fig. 1 Location of the Yangtze River Economic Belt, China

of emissions were mainly from the China Statistical Yearbook of the Environment and the China Environmental Yearbook (National Bureau of Statistics of China, 2012–2016b;d); socio-economic data mainly came from the China Statistical Yearbook for Regional Economy and the China City Statistical Yearbook (National Bureau of Statistics of China, 2012–2016a;c). For the city units with incomplete statistics in each yearbook, we further obtained statistical yearbooks of the provinces or cities in which the provinces are located. In addition, administrative division data were obtained from the National Basic Geographic Information System website (http://www.ngcc.cn/).

2.2 Methods

2.2.1 Environmental pollution load index

Rapid urbanization and industrialization process will bring large-scale pollutant emissions. Among the water and air pollutants, the two water pollutants COD and NH_3-N, and the two air pollutants SO_2 and NO_x are the chief pollutants in the water and air environment, which seriously threaten the stability of the ecosystem and human health. Therefore, in the environmental planning and control standards issued by the environmental department, these four types of pollutants have been used as the main indicators to identify environmental pollution load. In addition, these four kinds of pollutants come from a wide range of sources, such as residential lives, industrial manufacturing, agricultural production, transportation, and others. As indicators, they can comprehensively reflect the general degree of regional environmental load.

The EPLI based on the entropy method can be formulated as follows (Liu, 2019):

$$r_{ij} = \ln\left(a_{ij}\right) \tag{1}$$

$$r'_{ij} = \frac{r_{ij} - \min\left\{r_{ij}\right\}}{\max\left\{r_{ij}\right\} - \min\left\{r_{ij}\right\}} \tag{2}$$

$$R_{ij} = \frac{r'_{ij}}{\sum_{i=1}^{n} r'_{ij}} \tag{3}$$

$$E_j = -\frac{1}{\ln(n)} \sum_{i=1}^{n} R_{ij} \ln\left(R_{ij}\right) \tag{4}$$

$$G_j = 1 - E_j \tag{5}$$

$$W_j = \frac{G_j}{\sum_{j=1}^{m} G_j} \tag{6}$$

$$EPLI_i = \sum_{j=1}^{m} W_j r'_{ij} \tag{7}$$

where $EPLI_i$ represents the comprehensive environmental load situation in city i in the YREB. The larger the value is, the greater the environmental load is. a_{ij} is the emission amount of pollutant j (t) in the city i; r_{ij} is the attribute value after natural logarithm transformation.r'_{ij} is the attribute value of r_{ij} after maximum value normalization, $\max\{r_{ij}\}$ and $\min\{r_{ij}\}$ are the maximum and minimum value of r_{ij}, respectively. R_{ij} is the proportion of the r'_{ij} of the total. E_j is the entropy value of the pollutant j, G_j is the information utility value of the pollutant j, W_j is the entropy weight of the pollutants, n is the number of cities in YREB, m is the number of pollutants types.

2.2.2 Getis-Ord G^* index

Then, we use the local spatial autocorrelation Getis-Ord

G^* index to analyze whether there is a statistically significant high-value cluster (hot spot) or low-value cluster (cold spot) in the environmental pollution load on the city scale, and explore the agglomeration and dispersion patterns. The G^* index can be computed by the following equation (Getis and Ord, 1992; Ord and Getis, 1995):

$$G^* = \sum_{j=1}^{n} W_{ij} Y_j / \sum_{j=1}^{n} Y_j \quad (8)$$

In the equation, when i is not equal to j, the standard expression of G_i^* is:

$$Z\left(G_i^*\right) = \left[G_i^* - E\left(G_i^*\right)\right] / \sqrt{\mathrm{Var}\left(G_i^*\right)} \quad (9)$$

where Y_j is the EPLI of city j, $E(G_i^*)$ and $\sqrt{\mathrm{Var}\left(G_i^*\right)}$ are the expectation and variance of G_i^*, respectively. W_{ij} is the spatial weight matrix. If $Z(G_i^*)$ is positive and significant, it indicates that the value around city i is relatively high, making city i a hot spot where high values are concentrated. If $Z(G_i^*)$ is negative and significant, it indicates a cold spot where low values are concentrated.

Considering the density of cities and economic development level in different regions within the YREB are different, this paper referred to the existing research experience and established a spatial weight matrix W based on the economic development differences and spatial distances among cities (Li et al., 2010).

$$W = W_d \mathrm{diag}(\overline{Y}_1/\overline{Y}, \overline{Y}_2/\overline{Y}, ..., \overline{Y}_i/\overline{Y}, ..., \overline{Y}_n/\overline{Y}) \quad (10)$$

where W_d is an inverse distance spatial weight matrix, which can be defined as follow:

$$W_d = \begin{cases} 1/d & i \neq j \\ 0 & i = j \end{cases} \quad (11)$$

where d is the distance between geographical centers in city i and city j. $\overline{Y}_i$ is the average GDP of city i during the study period, $\overline{Y}_i = \frac{1}{(t_1 - t_0 + 1)} \sum_{t_0}^{t_1} Y_{it}$, $\overline{Y}$ is the average GDP of all cities in the study period, $\overline{Y} = \frac{1}{n(t_1 - t_0 + 1)} \sum_{i=1}^{n} \sum_{t_0}^{t_1} Y_{it}$, and t is the research year, t = 1 or 2 in this study.

2.2.3 Spatial econometric model

Considering the possible spatial interaction effects between the factors, the use of the spatial lag model (SLM), spatial error model (SEM), and spatial Durbin model (SDM) to estimate the parameters is proposed (Anselin, 1988; Elhorst, 2010).

When there is an endogenous interaction effect (WY), it is necessary to add a spatial lag of the explained variable to the general linear regression model to transform it into an SLM. The formula is expressed as follows:

$$Y = \mu WY + \alpha I_N + X\beta + \varepsilon; \varepsilon \sim N(0, \delta^2 I_N) \quad (12)$$

If there is an interaction effect in the error term ($W\mu$), namely, the model error term is spatially autocorrelated, it is necessary to add the spatially correlated error term and transform the model into the SEM. Then, the expression can be transformed as follows:

$$Y = \alpha I_N + X\beta + \lambda W\mu + \varepsilon; \varepsilon \sim N(0, \delta^2 I_N) \quad (13)$$

A more general SDM, which includes both endogenous interaction effects (WY) and exogenous interaction effects (WX), can be obtained by synthesizing the SLM and SEM. The expression is as follows:

$$Y = \mu WY + \alpha I_N + X\beta + WX\theta + \varepsilon; \varepsilon \sim N(0, \delta^2 I_N) \quad (14)$$

where Y is the explained variable EPLI in this study; X is the exogenous explanatory variable matrix; I_N *is* the unit vector; α is the constant term coefficient; ρ is the spatial regression coefficient; λ is the spatial autocorrelation coefficient between the regression residuals; β and θ are the parameter vectors to be estimated; W is the spatial weight matrix; and ε is the random error vector. When θ = 0, the SDM collapses to a SLM; when $\theta + \rho\beta = 0$, the SDM collapses to a SEM. The model utilizes the maximum likelihood (ML) method for parameter estimation. In view of the influence of exogenous explanatory variables on the local explained variables (direct effects) and the influence of exogenous explanatory variables on the adjacent explained variables (indirect effects), the optimal model is also be used to estimate the direct and indirect effects of each explanatory variable (LeSage and Pace, 2009; Elhorst, 2014).

The IPAT model is the basic framework for factor decomposition of environmental pollution load, which describes the relationship between environmental pollution load and population, affluence, and technological progress. STIRPAT model relaxes the assumption that each factor in the IPAT model changes in the same proportion. The stochastic STIRPAT model further extends the limitation of factor selection in the STIRPAT model, allowing researchers to incorporate more factors into the model to analyze the driving effect on the environmental pollution load and enrich the connotation of the model.

Thus, to analyze the spatial effect and driving relationship between environmental pollution load and main socio-economic factors, we refer to the stochastic STIRPAT model framework (Ehrlich and Holdren, 1971; Wang et al., 2019). Considering the availability of prefectural data, we select the population scale that reflects the population factor, the per capita GDP that reflects the economic development level, the industrialization level and agricultural economic share that reflect the industrial structure, the foreign direct investment and fixed asset investment that reflect the capital factor, and the population urbanization rate and land development intensity that reflect the urbanization process, and the local fiscal decentralization that reflects the level of localization as the explanatory variables. The variables are processed in the logarithmic form to reduce heteroscedasticity, and the final panel regression model is set as follows:

$$\ln EPLI_{it} = \alpha_{it} + \beta \ln TP_{it} + \gamma \ln UR_{it} + \delta \ln PGDP_{i}t + \xi \ln IS_{it} + \eta \ln AP_{it} + \theta \ln FDI_{it} + \mu \ln FAI_{it} + \kappa \ln LDI_{it} + \xi \ln FD_{it} + \varepsilon_{it} \quad (15)$$

where i is city i, t is the research year, t =1 or 2 in this study; α_{it} is the constant term coefficient; β, γ, δ, ζ, η, θ, μ, κ, and ξ are the regression coefficients; ε_i is the error term. The descriptive statistics of the variables in the model are shown in Table 1.

2.2.4 *k-medoids cluster method*

The *k*-medoids clustering method can automatically divide the data into *k* groups according to the nearest principle (Gu et al., 2020). Based on selecting the initial clustering center, the final group is determined by iterating according to the distance rules from each sample to the sample center. The *k*-medoids clustering method mainly includes three steps: 1) Select *k* elements in the system randomly as seed elements for *k* groups; 2) Assign the remaining elements to the nearest central element and redefine the new center of the group based on the distance principle; 3) Iterate step 2 until the samples contained in each group are stable.

To define the key element *k* in the *k*-medoids method, a common criterion is to use the elbow point of the variation of the ratio of the total between-group sum of squares (BSS) to the total sum of squares (TSS), namely

Table 1 Descriptive statistics of variables in the model

Variables	Meaning	Unit	Year	Mean	SD	Min.	Max.
EPLI	Environmental pollution load index	/	2011	0.55	0.15	0.08	0.99
			2015	0.52	0.14	0.07	0.97
PGDP	Per capita GDP	yuan (RMB)/person	2011	38035.60	28554.33	8842.56	106967.51
			2015	49227.54	36676.17	11426.12	140983.36
AP	The proportion of added value of the primary industry in GDP	%	2011	14.27	7.71	0.65	32.24
			2015	12.96	6.78	0.44	28.95
IS	The proportion of added value of the secondary industry in GDP	%	2011	50.43	9.52	25.62	75.54
			2015	46.79	8.56	22.76	71.45
FAI	The total investment in fixed assets	10^8 yuan (RMB)	2011	859.08	1141.47	49.07	7579.45
			2015	1884.26	1950.19	97.69	15367.97
UR	Population urbanization rate	%	2011	45.07	15.61	7.37	89.30
			2015	51.65	12.65	28.06	87.60
TP	Total population at the year-end	10^4 Person	2011	448.54	360.05	40.30	2919.00
			2015	458.35	370.32	40.80	3016.55
FDI	The amount of foreign direct investment	10^4 US dollar	2011	8.18	18.77	0.009	126.01
			2015	10.29	22.87	0.0005	184.59
LDI	Land development intensity	%	2011	10.15	7.61	0.23	46.51
			2015	10.63	7.89	0.24	48.12
FD	The ratio of local general fiscal budget revenue and general fiscal budget expenditure	%	2011	0.53	0.25	0.09	1.14
			2015	0.56	0.26	0.09	1.54

ΔBSS/TSS, as the objective function. A higher value for BSS/TSS suggests a better separation of the clusters, so that if the optimal number of clusters has not been reached, the improvement in the objective function should be substantial, but as soon as the optimal *k* has been exceeded, the curve flattens out.

3 Results

3.1 Spatial patterns of environmental pollution load

During 12th Five-Year Plan period (2011–2015), the average EPLI value of cities in the YREB dropped from 0.546 to 0.521, which was a decrease of 4.8%. Spatial differences and correlations at the subbasin and city level were as follows:

3.1.1 At the watershed and provincial scales

From upstream to downstream, the average EPLI value increased in sequence. In 2015, the average EPLI values in upstream, midstream, and downstream regions were 0.453, 0.539, and 0.578, respectively. Further analysis of the EPLI values of the secondary basins found that (Fig. 2), the EPLI in the Jinsha River subbasin, Mintuo River subbasin, and Jialing River subbasin in upstream were all lower than the overall average, the three were only 67.38% ,87.92%, and 88.53% of the average EPLI value of the YREB in 2015, respectively. From the Wujiang River subbasin to the east, the EPLI values of all subbasins were higher than the average value of the YREB. Among them, the environmental pollution load was more prominent in the Upper Mainstream subbasin, the Taihu Lake subbasin, and the Lower Mainstream subbasin. The EPLI of the Upper Mainstream subbasin in 2011 and 2015 were 0.734 and 0.695, respectively, which were 1.34 times and 1.33 times the average value of the YREB. And the EPLI in the Taihu Lake subbasin were 0.697 and 0.654, respectively, which were 1.27 times and 1.25 times the average value. The high environmental pollution load in the Taihu Lake subbasin and the Upper Mainstream subbasin may be mainly related to the dense distribution of population and industrial activities in these two highly urbanized basins.

The statistics of EPLI at the provincial level also showed that the environmental pollution load in midstream and downstream was significantly higher than that in upstream (Table 2). In 2011 and 2015, the average EPLI values of provinces in midstream and downstream were 0.588 and 0.561, respectively, which were 1.24 times that of the upstream provinces. In addition, the degree of environmental pollution load in municipalities was much higher than that of other provincial administrative regions. In 2015, the EPLI values of Shanghai and Chongqing were 0.898 and 0.972, respectively, which were 1.75 and 1.89 times the average EPLI values of other provinces in the same year. The municipality had a larger population and industrial scale, and the urbanization level was relatively higher, so their environmental pollution load levels were higher than those of prefecture-level cities. As for the changes of EPLI, the EPLI of each province had declined in 2011–2015, but the three provinces with the largest decline were all

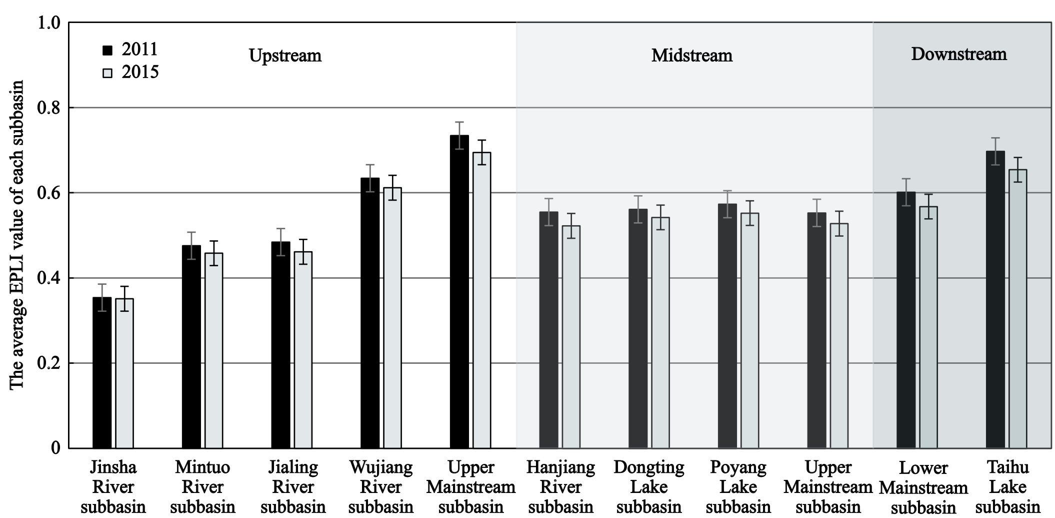

Fig. 2 Changes in environmental pollution load index (EPLI) in the subbasins in the Yangtze River Economic Belt

Table 2 Statistics of environmental pollution load index (EPLI) changes in provinces in the Yangtze River Economic Belt

Basin	Province/Municipality	2011	2015	Change rate / %
Upstream	Chongqing	0.996	0.972	–2.432
	Sichuan	0.473	0.453	–4.188
	Yunnan	0.400	0.382	–4.449
	Guizhou	0.548	0.524	–4.426
Midstream	Jiangxi e	0.568	0.549	–3.437
	Hubei	0.553	0.526	–4.924
	Hunan	0.574	0.555	–3.161
Downstream	Shanghai	0.945	0.898	–4.985
	Jiangsu	0.676	0.636	–5.872
	Zhejiang	0.599	0.567	–5.389
	Anhui	0.543	0.518	–4.621

downstream provinces, including Jiangsu, Zhejiang, and Shanghai. The average EPLI value in Jiangsu and Zhejiang had declined by more than 5%. The changes in EPLI indicated that the decrease in environmental pollution load in the YREB mainly came from the drop of pollution stress in the original high stress areas. The discharge reduction effect in original high load areas led to the decline of the overall level of pollution load in the region.

3.1.2 At the prefecture-level scales

From low to high, the EPLI of each city was divided into five levels according to the order of 0–0.20, 0.21–0.40, 0.41–0.60, 0.61–0.80, and 0.81–1.00, and the spatial distribution of each level was shown in Fig. 3. During 2011–2015, the environmental pollution load in the YREB was generally stable and partially improved. In 2011, the cities with high EPLI levels included Shanghai, Suzhou, and Xuzhou in downstream, and Chongqing in upstream. By 2015, the number of cities with high EPLI level was reduced to 2, and Xuzhou and Suzhou were dropped to sub-high level. The number of cities with high and sub-high EPLI levels decreased from 50 to 38 during 2011–2015, a decrease of nearly 1/4. By comparing the spatial distribution, it was found that the continuous distribution pattern of cities with high EPLI levels in each basin did not change significantly during the 12th Five-Year Plan period. The downstream area was the main distribution area of high EPLI level cities, and the proportion of high and sub-high EPLI level cities was close to 50% (48.00% and 47.37%). From the distribution of low and sub-low EPLI levels cities, it was mainly located in upstream of Sichuan and Yunnan provinces, and also scattered in the cities of midstream and downstream regions of Zhangjiajie, Xiangxi, Huangshan, Chizhou, Yingtan, Lishui, and Suizhou. Superimposing the provincial administrative boundaries, it was also found that high and sub-high EPLI level cities were mainly distributed along the borders of Yunnan, Sichuan, Guizhou, Chongqing, Hunan, Hubei, Jiangxi, Jiangsu, Zhejiang, Shanghai, and Anhui, showing significant boundary direction feature. It was noteworthy that along the border areas of Honghe-Kunming-Qujing-Bijie-Zunyi-Chongqing, a banded area of environmental pollution load had been formed. The area was located in the ecologically sensitive area of the Jinsha River subbasin and the Upper Mainstream subbasin of the Yangtze River, which was the key part of the ecological environment protection pattern of the YREB. Therefore, a more stringent negative list of environmental access and means of pollutant reduction should be implemented in this zone.

The global spatial autocorrelation analysis of the EPLI showed that the global Moran's I values in 2011

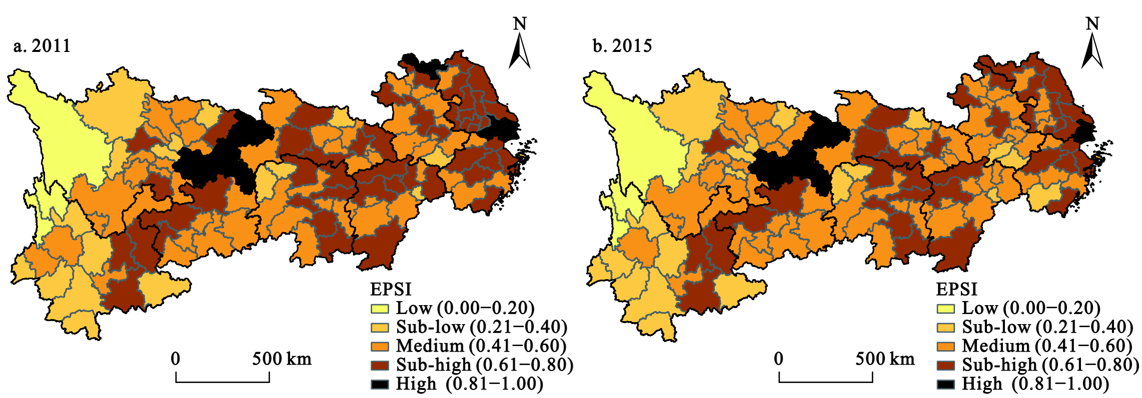

Fig. 3 Spatial distribution of environmental pollution load index (EPLI) at the prefecture-level in Yangtze River Economic Belt

and 2015 were 0.345 and 0.334, respectively, and both were positive and significant at 1% (Fig. 4), indicating a significant positive spatial correlation between environmental pollution load. Furthermore, the Getis-Ord G^* index was calculated and classified into four types from high to low: hot spots, sub-hot spots, sub-cold spots, and cold spots, and the spatial distribution of changes in hotspots of EPLI in the YREB was shown in Fig. 5. The agglomeration of high-value cluster and low-value cluster of EPLI in the YREB were quite significant and stable. Only nine cities had a change in the type of hot spot of EPLI. And four cities with increased heat were all located in the midstream of Hunan and Jiangxi provinces, indicating the risk of further concentration of environmental pollution load in midstream. The heat of environmental pollution load generally decreased from downstream to upstream. The hot spots of EPLI gathered in upstream, midstream, and downstream, forming a cluster pattern along the coastal, river, and provincial administrative boundaries. In downstream, the hot spots were mainly concentrated in the Yangtze River Delta, including the whole of Jiangsu Province and the coastal areas of Zhejiang Province. In midstream, the hot spots were located along the mainstream of the Yangtze River and the junction area of Hunan, Hubei, and Jiangxi provinces, and formed a trend of spreading along the river with the hotspots in downstream. In upstream, the hot spots gathered at the junction of Sichuan and Guizhou provinces. The sub-hot spots were concentrated around the hot spots, showing a

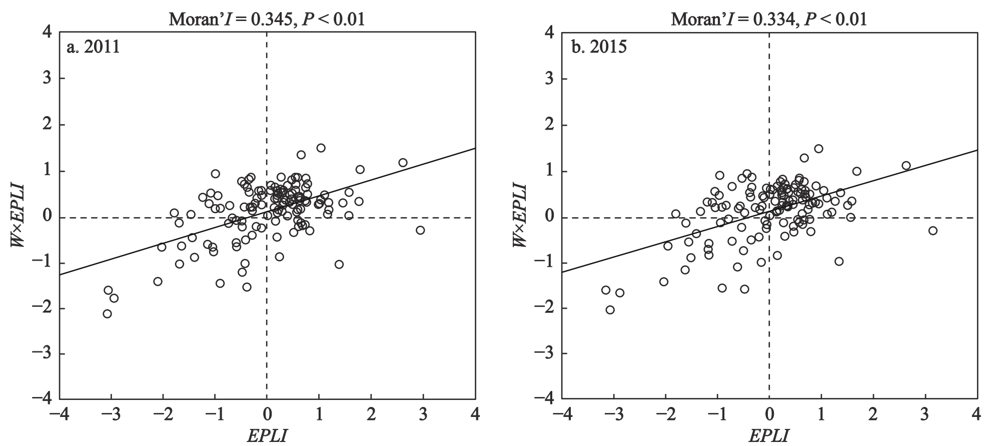

Fig. 4 Scatter plots of Moran'*I* of environmental pollution load index (*EPLI*) in 2011 and 2015 . *W* × *EPLI* indicates the spatial lag *EPLI* values of each city

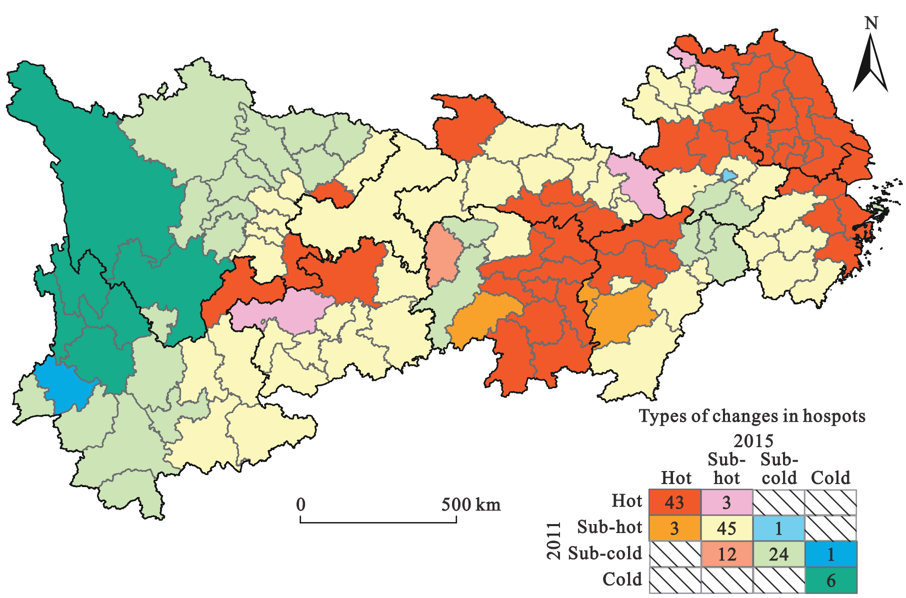

Fig. 5 Spatial distribution of changes in hotspots of environmental pollution load index (EPLI) in the Yangtze River Economic Belt

circle distribution pattern, including western Zhejiang Province, southern and northern Anhui Province in downstream, the whole territory of Hubei Province, and southeastern Jiangxi Province in midstream, and Chongqing, Guizhou provinces, and eastern Yunnan Province in upstream. The sub-cold spots and cold spots were mainly distributed in Sichuan Province and Yunnan Province in upstream and scattered in Hunan, Jiangxi, and Anhui provinces.

3.2 Drivers and spatial effects of environmental pollution load

3.2.1 Model specification and test

The LM tests were conducted for the SLM, SEM, and SDM models, and the results showed that the models have both spatial lag effect and spatial error effects. Furthermore, the result of the likelihood ratio test showed that the SDM model not only outperform the SLM model but also outperform the SEM model at 5% significance level.

When analyzing the drivers of the environmental pollution load in the YREB, due to the significant spatial autocorrelation of the residuals estimated by ordinary OLS method, the regression results estimated by the ordinary panel model would be obviously biased for the non-independent sample data. Therefore, the spatial panel model considering the spatial effect should be used for the estimation.

According to the Hausman test results, the fixed effect panel model rather than the random effect panel model should be adopted. Further, the joint significance test of spatial fixed effect and time fixed effect was necessary. The Likelihood ratio test (LR) results showed that at the 1% level, we rejected the null hypothesis of insignificant spatial fixed effects, but not the null hypothesis of insignificant temporal fixed effects. Therefore, the model should be extended to the spatial fixed effect model. According to the model criterion (Anselin, 1988), the applicability of the spatial lag model and the spatial error model is judged through the LM test and the robust LM test. The test results showed that at the 5% significance level, we rejected the null hypothesis of no spatial interaction effect between the explanatory variables of spatial lag and the error term, so the spatial Durbin model was adopted for regression estimation (Table 3).

3.2.2 Results of coefficient estimation

As shown in Table 4, the coefficients estimation results of the SDM model showed that, besides being positively driven by population size, industrialization level, land development intensity, and local financial autonomy, the positive driving effects of urbanization rate, agricultural economic share and foreign direct investment began to emerge at the end of the 'Twelfth Five-Year Plan' period. And the spatial lag coefficients also indicated that the environmental pollution load of the YREB would be significantly driven by population size, economic development level, industrialization level, agricultural economic share, foreign direct investment, and fiscal decentralization of neighboring cities.

The model estimation results also showed that there was a significant spatial effect of environmental pollution load in the YREB. The endogenous interaction of environmental pollution between adjacent cities had an impact on environmental pollution load in the YREB. In the SDM, the ρ value of the spatial lag term was positive and significant at 1% level. This meant that environmental pollution load had a positive spillover effect. That is, the increase in local stress would cause the stress of adjacent areas to increase.

3.2.3 Results of effect estimation

The results showed the spatial effect of the environmental pollution load and drivers in the YREB, which implied the drivers of environmental pollution load in the YREB have been spatially diverse. Furthermore, the direct, indirect, and overall effects of the SDM model are used to discuss the influence intensity of the explan-

Table 3 Diagnostic tests of spatial econometric models for drivers of environmental pollution load

Examining methods	Indexes	Statistics	*P*-value
Spatial autocorrelation test	Moran's *I* (error)	0.176	0.000
LM-test for spatial model	LM-lag	7.605	0.006
	Robust LM-lag	7.097	0.008
	LM-error	4.615	0.032
	Robust LM-error	4.107	0.043
Wald-test for spatial model	Wald-lag	26.125	0.002
	Wald-error	29.231	0.000
	LR-lag	26.346	0.002
	LR-error	29.864	0.000
Panel model test	Hausman	329.944	0.000
	LR-space	1030.809	0.000
	LR-time	–19.611	0.497

Table 4 Estimation results of spatial Durbin model for drivers of environmental pollution load

Variables	Coefficient estimates		Effects estimates		
	Main	*Wx*	Direct effect	Indirect effect	Total effect
ρ	0.609***				
	(0.074)				
ln*TP*	0.317***	0.276***	0.320***	0.310**	0.630***
	(0.035)	(0.089)	(0.037)	(0.129)	(0.139)
ln*PGDP*	–0.043	0.118**	–0.038	0.119**	0.080**
	(0.042)	(0.051)	(0.040)	(0.051)	(0.041)
ln*IS*	0.430***	–0.771***	0.427***	–0.771***	–0.344
	(0.072)	(0.232)	(0.067)	(0.268)	(0.257)
ln*AP*	0.059	0.129***	0.061	0.141***	0.202***
	(0.036)	(0.040)	(0.037)	(0.054)	(0.066)
ln*FDI*	0.011	–0.132***	0.011	–0.141***	–0.129***
	(0.014)	(0.041)	(0.013)	(0.050)	(0.047)
ln*FD*	0.195***	0.516***	0.197***	0.554***	0.751***
	(0.049)	(0.105)	(0.050)	(0.155)	(0.164)
ln*LDI*	0.046**		0.045**	0.002	0.047**
	(0.023)		(0.021)	(0.010)	(0.024)
ln*UR*	–0.009		–0.010	0.003	–0.007
	(0.058)		(0.056)	(0.013)	(0.060)
ln*FAI*	0.005		0.004	0.001	0.005
	(0.020)		(0.020)	(0.004)	(0.022)

Note: ***, **, and * indicate that the significance levels are 0.01,0.05, and 0.1 respectively. *Wx* indicated the spatial lag coefficients of the variables. In the modeling process, it was found that the spatial lag coefficients of ln*LDI*, ln*UR*, and ln*FAI* were not significant. In order to reduce the disturbance of insignificant variables to the model estimation results, the spatial lag terms are removed (Wu et al., 2021). The specific meaning of the variables could be seen in Table 1

atory variables, as shown in Table 4. There are three dominant factors, whose direct or indirect effect coefficient > 0.2 and passed the significance test, including population size, industrialization level, and fiscal autonomy.

(1) The population size had a significant positive promoting effect on both local and adjacent environmental pollution load. The direct and indirect effects of lnTP in the SDM model are 0.320 and 0.310, respectively, indicating that the population size is an important factor of environmental pollution load in the YREB. For every 1.000% increase in population size, the degree of local EPLI would increase by more than 0.320%, and the degree of adjacent EPLI would increase by 0.310%, indicating that the increase in population size has increased the emission base of various production and living pollutants, leading to an obvious rise in environmental pollution load of the local and adjacent cities.

(2) The industrialization level had a significant positive promoting contribution to the local environmental pollution load, while it had a significant negative effect on the environmental pollution load in the adjacent cities. In the SDM model, the direct and indirect effect of lnIS were both significant at 1% level. For every 1.000% increase in the proportion of the secondary industry, the local EPLI would increase by 0.427%, and the adjacent EPLI would decrease by 0.771%. The strong impetus of industrialization level in the local cities reflected a biased industrial structure in YREB, with a high proportion of pollution-intensive industries. And the significant negative driving effect of industrialization on EPLI in adjacent cities indicated that the spatial agglomeration of industrial activities in local cities would effectively attract economic factors such as population, raw materials, and industrial development opportunities of adjacent cities, reducing the material consumption and pollution emissions of adjacent cities. In addition, newly-built and renovated industrial projects

tented to have higher standards of pollution disposal technologies and environmental protection management, which had led to a decline in the production and discharge levels in adjacent cities.

(3) The local fiscal autonomy factor had a significant positive promoting effect. In the SDM model, the direct and indirect effects of lnFD were both positive and significant at 1% level, indicating that financial autonomy would promote the environmental pollution load in the YREB. Under the background of the current fiscal decentralization system, the improvement of fiscal decentralization had enabled local governments to obtain greater powers of affairs and capital control (Shen and Fu, 2005; Li and Zhou, 2005). Local governments actively promoted economic growth in pursuit of more fiscal revenue in decentralization contracts, which were willing to lower the threshold of local environmental protection and relax environmental regulations (Zhang et al., 2017; Xu et al., 2017). Finally, the local governments would show a characteristic of 'race to the bottom' in environmental access to get the priority of economic development.

Influence intensity of other drivers. The results of the SDM model showed that for every 1% increase in economic development and agricultural economic share, the degree of the environmental pollution load in adjacent cities would increase by 0.119% and 0.141%, respectively. For one thing, due to the economic competition among local governments, economic development in local cities might prompt neighboring local governments to relax environmental restriction policies to attract more investment, thereby triggering more pollution emissions. For another, administrative boundaries usually divide the same range of agricultural land into two different units, but due to the scale of agricultural production and geographical environment, local agricultural production often leads to the common development of neighboring areas. In addition, since agricultural lands were generally more likely to be distributed along urban boundaries, the free-rider behaviors that leads to pollution emissions might result in increased pollution emissions in adjacent cities. However, the indirect effect of the foreign direct investment had a clear negative contribution. For every 1% increase in the scale of foreign direct investment, the degree of the environmental pollution load in adjacent cities would decrease by 0.141%. Through the demonstration effect, the energy saving and cleaner production technology of foreign enterprises improved the production efficiency of neighboring enterprises, reduced the input of resource factors, thus lowering the environmental pollution load of adjacent cities. Besides, the intensity of land development had a significant positive direct effect, namely, the increase of land development intensity would aggravate the local environmental pollution load to some extent. In general, construction land has a higher pollution emissions intensity, which indicates that the intensive land development process will deteriorate the regional environmental pollution situation.

3.3 Zoning control of the environmental pollution load

3.3.1 Comprehensive zoning

The main drivers of cities in YREB were identified using *k*-medoids clustering method, setting the number of clusters from 2 to 11, and calculating the variation of BSS/TSS (ΔBSS/TSS) under each clustering model (Table 5). The results showed that when the number of clusters exceeded 7, the optimization effect of increasing clusters is no longer obvious. Therefore, we set the number of clusters $k = 7$ for clustering analysis.

By counting the mean values of the drivers within each cluster and processing them with maximum standardization, the differences in the drivers of each cluster could be compared. Further superimposed on the distribution of different types of functional zones in the YREB, the clusters could be divided into the following seven types (Figs. 6 and 7).

Table 5 Classification basis of *k*-medoids cluster method

The number of clusters	BSS	BSS/TSS	ΔBSS/TSS
2	120.946	0.138	0.138
3	138.897	0.159	0.021
4	179.414	0.205	0.046
5	204.553	0.234	0.029
6	252.488	0.289	0.055
7	264.567	0.302	0.014
8	271.427	0.310	0.008
9	277.110	0.317	0.006
10	264.109	0.302	-0.015
11	298.973	0.342	0.040

Note: the BSS and TSS are the total between-group sum of squares and the total sum of squares, respectively

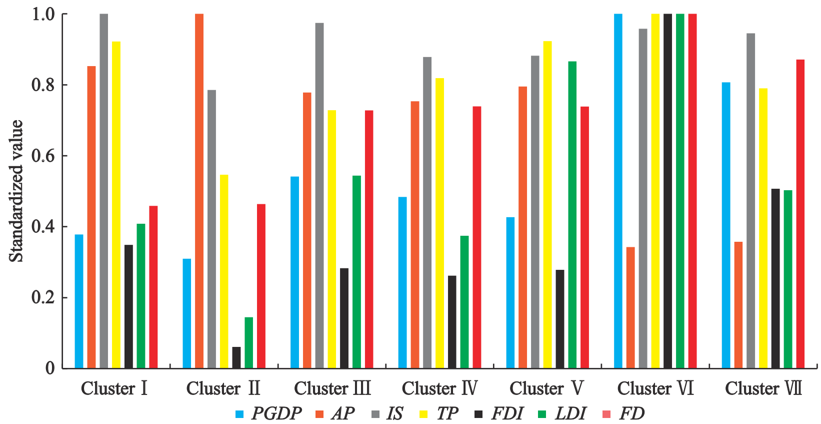

Fig. 6 The standardized values of means of drivers of environmental pollution load in the Yangtze River Economic Belt. The specific meaning of the variables were in Table 1.

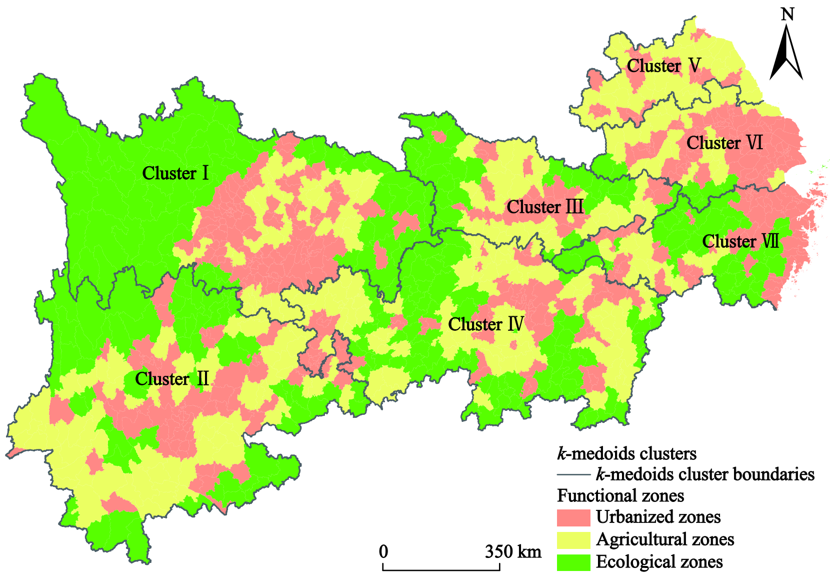

Fig. 7 Zoning map of environmental pollution load in the Yangtze River Economic Belt

Cluster Ⅰ was mainly distributed in the northwest of the YREB, including Chongqing Municipality, northern Yunnan Province and most of Sichuan Province. The level of economic development and localization of this cluster was not high, but the industrialization level and population size were in the forefront of the YREB. The urbanized zones and agricultural zones were mainly distributed in and around the Chengdu-Chongqing metropolitan circle in the east of the region. The area of urbanized zones was 1.64 times that of the main agricultural zones, and the area of ecological zones in this cluster accounted for the largest proportion, reaching 63.25%, the highest among all clusters. The pollution load in this cluster was mainly driven by the discharges from urban and rural residential living activities and industrial production activities, and could be defined as the upstream area dominated by industrial and living sources.

Cluster Ⅱ was located in the southwest of the YREB, including most of Yunnan Province and some cities in the western Guizhou Province. This cluster had the lowest level of economic development, population size and land development intensity among all regions, and the degree of localization was not high, and the degree of localization was not high, but the share of agricultural economy was prominent. The urbanized zones and agricultural zones were widely distributed in most of the cluster region, and the area of agricultural zones was 1.61 times larger than that of urbanized zones. The pollution load of this cluster was strongly influenced by agricultural production activities and could be defined as the upstream area dominated by agricultural sources.

Cluster Ⅲ was mainly distributed in the central and northern parts of the YREB, including most of Hubei Province and some cities in the southwestern Anhui Province. The industrialization level and land development intensity in this cluster were both high. The urbanized zones were concentrated along the mainstream of the Hanjiang River and the Yangtze River, and the pollution load within the cluster region was mainly influenced by industrial production and urban residential living activities, which could be defined as the midstream area dominated by industrial and living sources .

Cluster Ⅳ was mainly distributed in the central and southern regions of the YREB, including the eastern Guizhou Province, the whole Hunan Province and some cities in the southern Jiangxi Province. The population scale in this cluster was large, but other pollution load drivers such as economic development level, scale of foreign direct investment and land development intensity were not prominent in the YREB. The urbanized zones were mainly distributed in Changsha-Zhuzhou-Xiangtan metropolitan circle, and the agricultural zones were distributed along the periphery of the urbanized zones, which could be defined as the midstream area dominated by industrial, agricultural and living sources.

Cluster Ⅴ mainly included some cities in Anhui Province and the northern Jiangsu Province. The population scale and the land development intensity in this cluster were large, and the agricultural economic share was prominent. There were no ecological zones in this cluster, and the agricultural zones accounted for 76.02% of the total area. The pollution load in this cluster was significantly affected by residential life and agricultural production, and this cluster could be defined as the downstream area dominated by agricultural and living sources.

Cluster Ⅵ mainly included Anhui Province, the southern Jiangsu Province, and Shanghai Municipality. All drivers except agricultural economic share were prominent in this cluster. Population scale, industrialization level, and land development intensity all ranked at the top of the region. In addition, the influence of foreign direct investment scale and local fiscal decentralization were also significant. The urbanized zones were densely distributed in the YREB, and the pollution load was driven by multiple factors. This cluster could be regarded as the downstream area dominated by a mixture of industrial, agricultural and living sources under high economic growth.

Cluster Ⅶ included most of Fujian Province and the northern Jiangxi Province. This cluster had a high level of economic development and industrialization, a large population, and a high degree of localization. The urbanized zones were mainly distributed along the coastal line, and the area of urbanized zones relative to main agricultural production zones reached 2.42, which was the highest among all regions. Pollution load in the cluster were mainly influenced by activities of industrial production and urban residential life, so this cluster could be considered as the downstream area dominated by industrial and living sources.

3.3.2 Functional zoning control

Furthermore, regional differences in driving forces of environmental pollution load in the YREB should be considered, and targeted suggestions should be put forward according to local conditions for different types of cities.

For downstream areas, it should be paid high attention to comprehensive pollution stress caused by multiple factors in highly urbanized areas, and it is urgent to strengthen the construction of urban pollution treatment facilities and pipe network, improve the environmental shortcomings of the comprehensive carrying capacity. It is necessary to optimize the local performance evaluation system, incorporate local environmental gains and losses into the decentralized incentive mechanism.

For the midstream areas in the process of rapid urbanization, it is urgent to accelerate the transformation of the element-intensive industrialization mode, and attention should be paid to the pollution emission process in the industrial sector to enhance the exemplary role of green production technology and production philosophy in foreign enterprises. Especially in key sewage industries such as chemical raw materials and chemical products, non-metallic mineral products, agricultural and sideline food processing, metal smelting and rolling processing, electric power, and thermal power production and supply, it is urgent to adjust the industrial structure and spatial structure, and increase the consideration of environmental benefits and emission reduction targets in production technology.

For the upstream areas with low urbanization rate and mainly agricultural and ecological zones, it is necessary to improve the threshold of regional environmental access, and pay attention to the high pollution stress from industrial enterprises in the process of industrialization, to avoid becoming a pollution paradise for high-pollution industries. For agricultural source dominated areas, farmers should be guided to adopt cleaner production methods to control agricultural non-point source pollution from the source. At the same time, the micro, ecological, and decentralized treatment mode should be explored to promote the local treatment of environmental pollutants. For ecological zones within the region, the main control is to control the emissions of urban and rural residential living sources to reduce the direct discharge of pollutants.

For the YREB region, the upstream and downstream regions should strengthen joint pollution prevention and treatment by strengthening the environmental transfer payments in the downstream and apply them to the construction of environmental infrastructure, pollution control and emission reduction technology in the midstream and upstream, to reduce the cross-regional flow of pollution.

4 Discussion

The process of environmental pollution load has a significant spatial spillover effect in the YREB, and the increase of local stress will also cause the intensification of neighboring stress. The reasons for this spatial spillover effect may lie in two aspects. On the one hand, because adjacent regions are usually in the same regional economic division of the labor system, local and adjacent regions have similarities in industrial structure, production costs, and markets. If local pollution-intensive industries are difficult to clean, then the discharge reduction of adjacent cities will also be negatively affected. On the other hand, the nearby transfer of pollution effect is widespread. Affected by the increasing returns to scale, consumer preferences, and logistics costs, the pollution-intensive industries are more inclined to move to adjacent regions rather than perform large-scale spatial transfers, even if they relocate.

This study focuses on the comprehensive stress process of a regional environmental system caused by various man-made pollutants. In fact, environmental pollution load is a complex process of interaction between natural and human factors. In the future, it is necessary to study the response and adaptation of natural factors after receiving pollution from the aspects of environmental carrying capacity and threatened response of environmental pollution load. And the specific mechanism of the spatial effect of environmental pollution load and the internal mechanism of spatial interaction among drivers remains to be further studied from the micro-enterprise level. At the same time, in the follow-up study, it is necessary to further reveal the temporal and spatial process and influence of environmental pollution load under the attributes of cross-border, upstream and downstream, and mainstream and tributaries. In addition, due to the limitations of data acquisition, the research period of this paper is relatively short. In the future, based on the second national pollution source census, long-term and multi-category pollution emission research can be carried out to further explore the response of environmental pollution load under strong environmental control policies.

5 Conclusions

The results showed that the degree of environmental pollution load in the YREB decreased by 4.8% from 2011 to 2015 and revealed a gradient increasing trend from upstream to downstream. The downstream area was the main distribution area with high pollution load, and the process of high pollution load in cross-border areas of provincial administrative boundaries deserved attention.

The degree of local environmental pollution load in the YREB is affected by the surrounding cities. Population, industrialization, and fiscal decentralization are the three dominant factors affecting the EPLI in the YREB. Population and fiscal decentralization not only drive the increases in the local EPLI but also positively act on the surrounding areas through the spatial spillover effect. As for other drivers, land development intensity mainly drives the increase in the local EPLI in the YREB, and factors such as economic development level and agricultural economic share can only act on the increase in the adjacent EPLI, while the foreign capital shows a negative effect on the adjacent EPLI.

The drivers of environmental pollution load in the YREB have been diversified in space. According to the differentiation characteristics of drivers of each city, the YREB region can be divided into seven areas. Which are the upstream area dominated by industrial and living sources in the northwestern YREB, the upstream area dominated by agricultural sources in the southwestern YREB, the midstream area dominated by industrial and living sources in the northern YREB, midstream area dominated by industrial, agricultural and living sources in the southern YREB, the downstream area dominated by agricultural and living sources in the northeastern YREB, the downstream area dominated by a mixture of industrial, agricultural and living sources under high economic growth in the eastern YREB, and the downstream area dominated by industrial and living sources in the southeastern YREB.

The policy implication of this study mainly consisted of the following two aspects: 1) Because of the spatial spillover effect of environmental pollution load, we should cooperate to establish deep environmental regulations such as environmental access, pollution payment, and cross-border early warning, promote the value of environmental capacity across regions, and promote the sewage charge system that pays equal attention to both concentration and total amount, to minimize the degree of environmental pollution load while realizing social and economic development. 2) The YREB has been in the process of rapid urbanization and industrialization for a long time. The cumulative superposition of production and life, urban and rural, endogenous, and cross-regional sewage discharge leads to severe environmental pollution load. It is urgent to take the environmental carrying capacity and pollution stress degree as important considerations for the development and protection of the YREB, and accelerate the transformation of the development mode of the YREB into ecological civilization. The specific policy enlightenment also includes: formulating differentiated industry access lists combined with different major function orientation of each cluster area, giving full play to the leading role of environmental regulation in development and protection activities, embedding regulatory requirements into productivity layout and planning, and formulating pollutant emission limits, environmental quality targets, and emission reduction incentive mechanisms according to the degree of environmental pollution load, to form a more targeted pollution source governance system.

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