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Impact of Economic and Environmental Factors on O_3 Concentrations in the Yangtze River Delta Region of China

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Abstract: The concentration of atmospheric ozone (O_3) pollution is showing a rapid growing tendency, and O_3 pollution has become one of the bottleneck issues that restrict the continuous improvement of air quality in China. In this study, we first identified the primary factors based on the source apportionment of O_3, then used factor analysis to divide these selected factors into economic and environmental categories. The geographical detector model was used to analyze the impact of factors and their interactions on O_3 concentration in 41 cities in the Yangtze River Delta (YRD) region in 2020. The results showed that forest coverage ranked first among all the detected factors, suggesting a strong relationship between the regional O_3 concentration and forest coverage. The driving factors of economic activity were ranked as follows: actual utilization of foreign capital (0.400) > gross domestic product (GDP) per capita (0.387) > proportion of tertiary industry (0.360) > urbanization rate (0.327) > per capita consumption expenditure (0.194) > research and development (R&D) of full-time equivalents of industrial enterprises above designated size (0.182) > number of industrial enterprises (0.126). The interaction between any two factors enhanced their influence on O_3 concentration more than any single factor, indicating that the variability of regional O_3 concentration was an outcome of a combination of multiple factors. This study could provide recommendations for the prevention and control of O_3 pollution and the development of ecological integration in the YRD region.

Keywords: O_3 concentration; economic and environmental factors; geographical detector model; Yangtze River Delta Region

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1. Introduction

Ozone (O_3) pollution has emerged as a critical and pressing environmental challenge in China [1–3], with its severe impact offsetting the previous benefits achieved through effective control measures for sulfur dioxide (SO_2), nitrogen oxides (NO_x), and fine particulate matter ($PM_{2.5}$) [4–6]. The distribution of O_3 pollution in China exhibits significant regional and temporal variability, with more severe O_3 pollution detected in eastern China [5,7], the maximum concentration of O_3 found to be higher in southern cities than in northern cities, and notable differences in the timing of peak hourly mass concentrations between eastern and western cities [8,9]. As one of the urban agglomerations with the largest population and the most developed economy, the YRD urban agglomerations are the most polluting area of O_3 pollution [1,10,11].

There are numerous factors associated with O_3 contamination. Social and economic activities play a key role in driving pollutant emissions into the environment. The quantitative analysis methods of Kriging interpolation, spatial autocorrelation analysis, and geographic detection are commonly used to explore the impact factors of O_3 concentration [12,13]. The spatial differentiation of O_3 concentration in the YRD is mainly driven by socio-economic factors [14–16]. It has been known that volatile organic compounds (VOCs), nitrogen oxides

(NOx), carbon monoxide (CO), methane (CH_4), and other substances play crucial roles in the formation of O_3 [17–20], and industrial combustion has been identified as the largest source of O_3 generation rate [3,21]. As a result, except for the industrial factor, per capita consumption expenditure, which could reflect the situation of household cars and appliances in the region, can be considered an indispensable factor to evaluate the concentration of O_3 [22]. The extremely complex interaction between urbanization and the ecological environment has been discovered [23]. By establishing a regression model of the Kuznets curve of space, the level of air pollution continued to rise with the continuous growth of per capita GDP [24]. Therefore, the per capita GDP served as a crucial indicator that influences environmental quality, which effectively reflects the economic development stage of an economy and plays an essential role in determining the level of air pollutants [25]. The significant positive correlation between foreign direct investment (FDI) and air pollution in China has been reported; with a 1% increase in FDI, air pollution increases by 0.0235% [26]. But some researchers also point out that FDI has improved the air quality in China [27]. Consequentially, exploring the relationship between FDI and O_3 concentration in the YRD region is of great significance. Factors of the development of science and technology, for example, the R&D full-time equivalent of industrial enterprises above a designated size, play an influential role in the mitigation of environmental pollution [28,29]. Compared with other environmental factors, forest coverage could better reflect the ecological environment of the city [30].

Understanding the driving mechanisms behind O_3 emissions and identifying key contributors can facilitate the development of strategies to mitigate O_3 emissions and reform policies. Most studies have primarily focused on the impact of climate change, meteorological factors, source apportionment, and inter-regional and inter-city transport on O_3 pollution [1,15,29,30]. Although socioeconomic factors such as economic size, urbanization, and emission sources have been examined for their influence on O_3 concentration in YRD regions [14–16], the specialized research on the role of social factors and their interplay in influencing O_3 concentration is insufficient. During the research, 41 cities in the YRD were selected as study areas. The actual use of foreign investment, per capita GDP, per capita consumption expenditure, urbanization rate, R&D full-time equivalent of industrial enterprises above the designated size, number of industrial enterprises above the designated size, proportion of tertiary industry, and forest coverage were chosen as impact factors. The data were processed by the ArcGIS technique, which involved superimposition and discretization processing, followed by a quantitative analysis of the contributions and interactions of each factor using the geographic detection software. Finally, based on our results, we proposed scientifically plausible measures to control O_3 concentration in order to provide a theoretical basis for quantitatively understanding the social factors affecting O_3 concentration and their interaction mechanisms in YRD.

2. Methods and Data Analysis

2.1. Research Area

The YRD is located on the lower reaches of the Yangtze River and the coast of the East China Sea (114°54′–122°12′ east longitude, 27°02′–35°20′ north latitude), with convenient land and sea transportation conditions (Figure 1), which is the important intersection area of the "Belt and Road" and the Yangtze River Economic Belt [31]. According to the National Bureau of Statistics (http://www.stats.gov.cn, accessed on 1 May 2023), the GDP of the YRD region accounts for about one-fourth of China's total GDP. The more the economy grows, the more the ecological environment is negatively affected. The annual average concentration of O_3 was 100 ug·m^{-3} in 2020. Major cities in the YRD have adopted O_3 as the primary air pollutant, and 46.3% of cities have exceeded the standard for O_3 pollution. This research area covers 41 urban clusters, which are stipulated in the outline of the Yangtze River Delta Regional Integrated Development Plan.

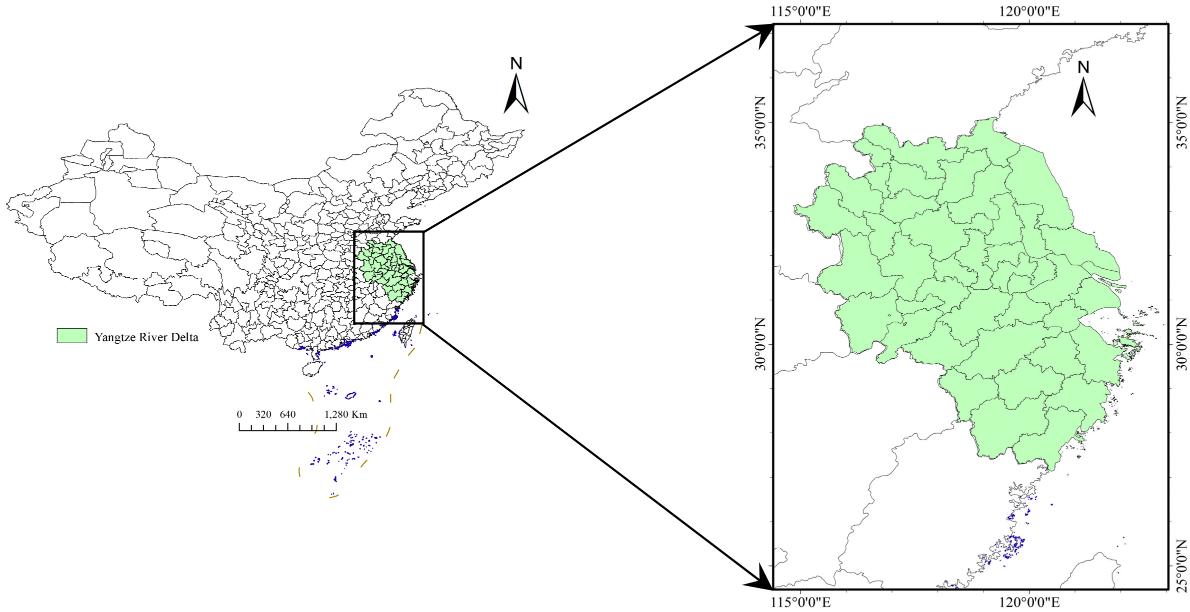

Figure 1. Central urban clusters in Yangtze River Delta.

2.2. Social Factors

During the study, the selection of indicators was guided by the following principles: (1) fit with the research object; (2) could be evaluated by existing data; (3) avoided overlap and strong correlation between each indicator.

Coupling effects arising from the interaction and mutual influence of two or more systems could be avoided by eliminating quantitative indicators for which data could not be collected, removing qualitative indicators that are difficult to quantify, and simplifying indicators with repetitive content. As shown in Table 1, to improve the accuracy of the research, this study selected per capita GDP, per capita consumption expenditure, actual use of foreign investment, R&D full-time equivalent of industrial enterprises above the designated size, number of industrial enterprises above the designated size, proportion of tertiary industry, urbanization rate, and forest coverage as research objects. Among them, the Per capita GDP reflects economic growth [15]; Per capita consumption expenditure is used to measure the consumption situation of residents [30]; the actual utilization of foreign investment represents for the openness of foreign trade [24]; the R&D full-time equivalent of industrial enterprises above designated size reflects the status of science and technology development [32]; Number of industrial enterprises above designated size is used to analyze the degree of regional industrialization development [33]; the proportion of tertiary industries stands for the level of economic development of tertiary industry; The urbanization rate presents the speed and extent of the urbanization process; and forest coverage serves as a crucial indicator that reflects the actual level of forest resources and land occupation in a country or region [30].

Table 1. Influencing factors for the concentration of O_3 in YRD region.

Number	Primary Indexes	Secondary Indexes	
1	Economic factor	Per capita GDP	X_1
2		Per capita consumption expenditure	X_2
3		Actual use of foreign investment	X_3
4		R&D full-time equivalent of industrial enterprises above designated size	X_4
5		Number of industrial enterprises above designated size	X_5
6		Proportion of tertiary industry (%)	X_6
7		Urbanization rate	X_7
8	Environment factor	Forest coverage	X_8

2.3. Data and Data Sources

Seven economic indicators (X_1–X_7) and one environmental indicator (X_8) were selected to reflect the study area (Table 1). The indicators of 2020 data were obtained from the Statistical Yearbook of Shanghai, Jiangsu, Zhejiang, and Anhui provinces, the ecological environment quality bulletin, and the National Bureau of Statistics (https://data.stats.gov.cn/, accessed on 3 May 2023), respectively.

2.4. Data Processing

2.4.1. Factor Analysis

Factor analysis is used to reduce the dimension of the original variables to the common and special factors, and the original variables are interpreted by the factors. A few factors coming from some variables with complicated relations can be obtained analytically, thus simplifying the complex problem. The factor analysis model was as follows:

$$\begin{cases} X_1 = a_{11}F_1 + a_{12}F_2 + \cdots + a_{1m}F_m + e_1 \\ X_2 = a_{21}F_1 + a_{22}F_2 + \cdots + a_{2m}F_m + e_2 \\ \vdots \\ X_p = a_{p1}F_1 + a_{p2}F_2 + \cdots + a_{pm}F_m + e_p \end{cases} \quad (1)$$

where X_1, $X_2 \cdots$, X_p are the observed random vector with number of p, a_{11}, a_{12}, …, a_{pm} are the factor loadings, and a_{pm} is the correlation coefficient between p variables and the m factor, describing the importance of variable in the factor. F is the common factor of X and independent from each other. e is the specific factor of X, and they are also independent of each other; furthermore, the factors of F and e are mutually independent.

2.4.2. ArcGIS Technology

ArcGIS overlay analysis is a spatial analysis method commonly employed in geographic information systems (GIS) to extract implicit spatial information. It involves superimposing multiple data layers representing different topics to generate novel data layers. The results of the overlay analysis integrate the attributes of elements in two or more layers to generate different attribute relations and spatial connections. Discrete methods are commonly used in GIS to transform continuous spatial data into discrete points, lines, or surfaces for enhanced spatial analysis and modeling [34].

2.4.3. Geographical Detector Method

A geographic detector is a spatial analysis model that can detect spatial differentiation and reveal the relationship between certain geographical attributes and their explanatory factors. The proposed method is capable of detecting the effect of individual factors on the spatial differentiation of dependent variables and performing statistical tests to determine their significance. It has been widely applied in various fields, such as environmental impact factor analysis and vegetation change driving force analysis. The geographical detector comprises four modules: fact or fact detection, interaction detection, risk detection, and ecological detection. Among them, factor detection involves the spatial differentiation of the dependent variable Y and the explanatory power of different factors X on the dependent variable Y. The degree of explanation is quantified by q. The purpose of interaction analysis is to determine whether the combined impact of any two influencing factors on the dependent variable Y is significantly different from the individual effect of a single influencing factor and to assess if these influencing factors independently affect the dependent variable Y. The types of interactions are presented in Table 2. During the research, the factor detection function is utilized to analyze the impact of various influencing factors on O_3 concentration in the YRD. The formula for the calculation is as follows:

$$q = 1 - \frac{\sum_{g=1}^{L} N_g \sigma_g^2}{N\sigma^2} \quad (2)$$

where N_g and σ_g^2 are the sample size and variance of layering g. The value of q represents the degree to which a certain factor explains the concentration of O_3, with a range from 0 to 1. A higher value indicates a stronger explanatory power of this factor on spatial differentiation in O_3 concentrations, while a lower value indicates a weaker explanatory power. More details are described by Wangle et al. (2010) [35].

Table 2. The type of interaction.

Conditions	Interaction
$q(X_1 \cap X_2) < Min(q(X_1), q(X_2))$	Nonlinearly, Weaken
$Max(q(X_1), q(X_2)) > Min(q(X_1), q(X_2)) < q(X_1 \cap X_2)$	Nonlinear, Weaken
$q(X_1 \cap X_2) > Max(q(X_1), q(X_2))$	Bivariate, Enhance
$q(X_1 \cap X_2) = q(X_1) + q(X_2)$	Independent
$q(X_1 \cap X_2) > q(X_1) + q(X_2)$	Nonlinearly, Enhance

3. Results and Discussion

3.1. Factor Analysis Results

The result of factor analysis showed that the KMO value was 0.735, indicating that it was reliable to explore various influencing factors through factor analysis (Table 3). Among the eight variables, factors F_1 and F_2 exhibited the highest eigenvalues of 4.505 and 1.360, respectively, contributing to a cumulative variance of 73.318% for the first two factors (Table 4), indicating that the basic model possessed sufficient explanatory ability. Two principal components were selected for further analysis. As shown in Table 1, the first principal component was the economic factors, and the second principal component was the forest coverage, which was classified as the environmental factors.

Table 3. KMO and Bartlett sphericity test.

KMO sampling suitability measure		0.735
Bartlett sphericity test	Approximate chi-square distribution	222.183
	df	28
	Sig.	0.000

Table 4. Total variance explained by principal component analysis.

Total Variance Explained									
Component	Initial Eigenvalue			Extraction Sum of Squared Loading			Rotation Sum of Squared of Loading		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
F_1	4.505	56.316	56.316	4.505	56.316	56.316	4.421	55.268	55.268
F_2	1.360	17.002	73.318	1.360	17.002	73.318	1.444	18.050	73.318
F_3	0.683	8.535	81.853						
F_4	0.533	6.662	88.514						
F_5	0.410	5.120	93.635						
F_6	0.304	3.801	97.436						
F_7	0.151	1.887	99.323						
F_8	0.054	0.677	100.00						

3.2. Results of Geographical Detector Analysis

The results of the factor test for the geographical detector are shown in Table 5. Correlation analysis was used to determine the impact of each numerical variable. A detection factor was considered to have a positive effect if it was positively correlated with O_3 concentration, and conversely, if the correlation was negative, the factor was considered to have a negative effect. The results showed that, apart from the positive effect of the actual utilization of foreign capital on the concentration of O_3, all other effects revealed a negative trend. The explanatory power of the eight driving factors for O_3 in the YRD ranged from 0.126 to 0.650, and the driving factors were ranked as follows: forest coverage (0.65) > actual utilization of foreign capital (0.400) > GDP per capita (0.387) > proportion of tertiary industry (0.360) > urbanization rate (0.327) > per capita consumption expenditure (0.194) > R&D full-time equivalent of industrial enterprises above designated size (0.182) > number of industrial enterprises (0.126).

Table 5. The results of factor detection.

		q Statistic	*p* Value
X_8	Forest coverage	0.650	0.000
X_3	Actual use of foreign investment	0.400	0.000
X_1	Per capita GDP	0.387	0.000
X_6	Proportion of tertiary industry	0.360	0.000
X_7	Urbanization rate	0.327	0.000
X_2	Per capita consumption expenditure	0.194	0.000
X_4	R&D full-time equivalent of industrial enterprises above designated size	0.182	0.000
X_5	Number of industrial enterprises above designated size	0.126	0.000

3.2.1. Environmental Factors

The spatial distribution of each influence factor in the 2020 YRD is illustrated in Figure 2. In the southern part of the delta, forest coverage was higher than in the northern part, and conversely, O_3 concentration was higher in the northern part and lower in the southern part. It was clearly demonstrated that forest coverage demonstrated the highest explanatory power (0.650) as an ecological environmental factor, indicating that it plays a crucial role in influencing atmospheric O_3 concentration levels within the YRD region. As an ecological environmental factor, it was clear that forest coverage had the highest explanatory power (0.650), indicating that it played a crucial role in influencing atmospheric O_3 concentration levels within the YRD region. It might be due to the surface characteristics of plant leaves, canopy characteristics, environmental factors, and green patches of different structural types that would affect the dust retention effect in the environment [36,37]. The higher the rate of forest coverage, the stronger the ability to retain water, reduce pollution, absorb harmful particles in the air, and purify the air. Therefore, the effective implementation of afforestation measures to enhance forest coverage was a crucial undertaking in mitigating O_3 concentration in the YRD region.

3.2.2. Economical Factors

Among the economic factors, the actual utilization of foreign capital in the Yangtze River Delta exhibited the highest explanatory power (q = 0.4). In 2020, the actual use of foreign investment in the central-eastern region of the Yangtze River Delta was relatively high, whereas it was comparatively low in the southern region (Figure 2). Although there were uncertain factors affecting the local environment, the substantial influx of foreign investment had stimulated employment and local economic growth. The introduction of foreign investment and the strengthening of clean production technologies could facilitate the mutual development of the environment and the economy. Over the years, the Yangtze River Delta region has continuously enhanced the quality of foreign investment, optimized its structure, revised traditional investment introduction evaluation indices, established foreign direct investment environmental effect evaluation indices, implemented a comprehensive regional environmental management system, and improved laws and regulations on pollution transfer resulting from foreign direct investments in China [38–40], thereby promoting coupled and coordinated development of the regional economic environment.

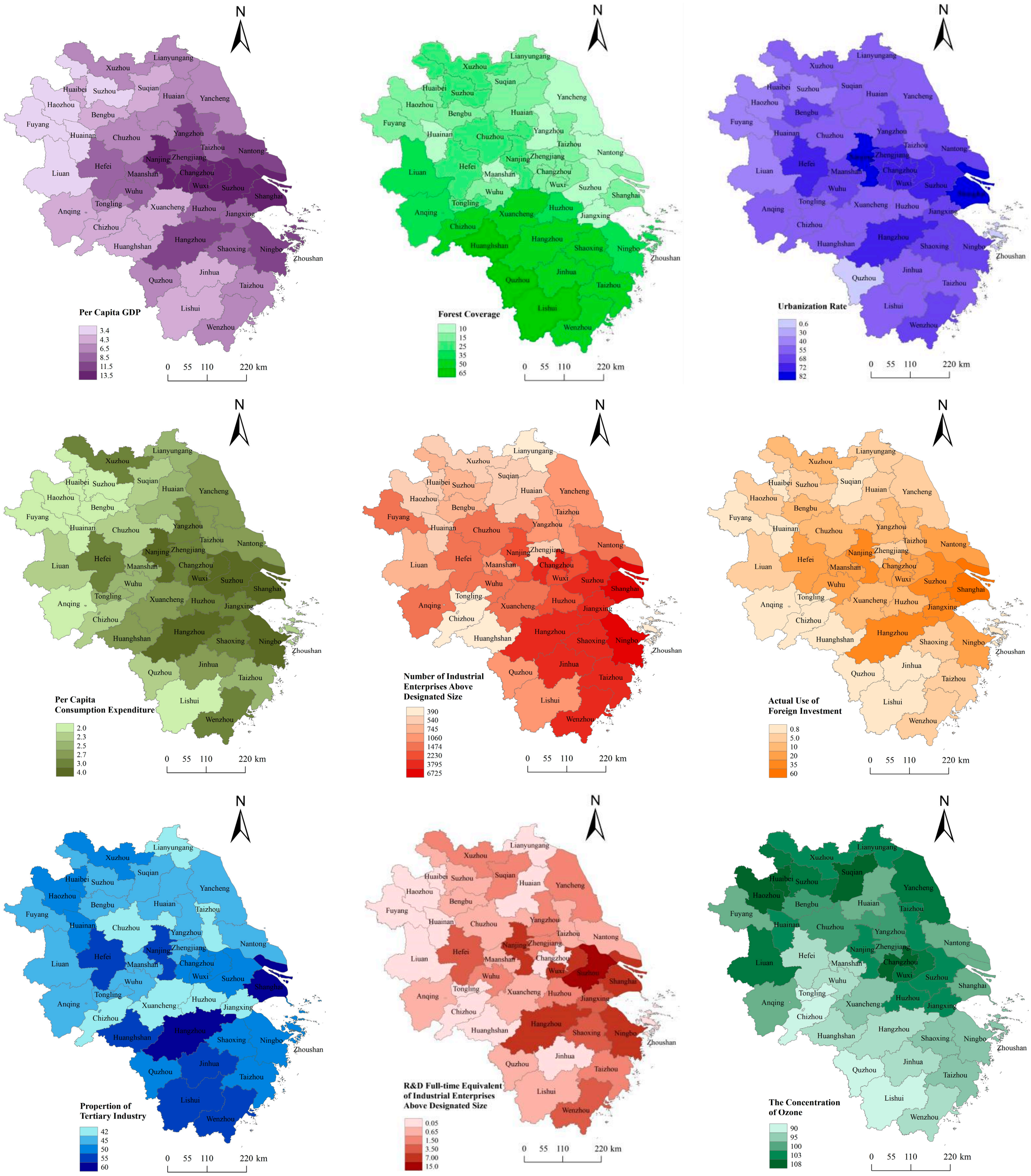

Figure 2. Spatial distribution of the impact factors and the concentrations of O_3 in the YRD region in 2020.

Per capita GDP is a crucial indicator for measuring economic development and living standards [41,42]. It had secondary explanatory power for environmental O_3 concentration among economic factors, suggesting that regional economic growth significantly affects O_3 concentration. Rapid economic growth over the past three decades has been accompanied by severe environmental pollution in the YRD region. It has been found that the relationship between environmental pressure and economic growth exhibits an inverted U-shaped curve, whereby economic development leads to a gradual deterioration of environmental quality during the low-income phase, whereas, after reaching a certain level of economic development, environmental quality begins to improve [43]. Furthermore, numerous studies have demonstrated the significant impact of per capita GDP on sulfur dioxide (SO_2) and nitrogen oxide (NO_x) emission intensity. The relationship between economic growth and some environmental pollutants (SO_2, NO_x, and dust) also showed an inverted U-shaped relationship, which also presented an increased tendency at first and then a decreased tendency [44,45]. The explanatory powers of tertiary industry and urbanization rates were 0.36 and 0.327, respectively. The adjustment of the industrial structure expedited the process of urbanization. As urbanization progressed, there was an increasing demand for capital, labor, science, and technology, which promoted production and economic growth. However, this also led to an increase in rigid energy consumption requirements and total pollutant emissions, resulting in ecological and environmental issues such as water, air, soil, and solid waste [46,47]. Based on the analysis of provincial panel data from 2003 to 2015, an increase in the proportion of tertiary industries in China was found to have a mitigating effect on haze pollution [48,49]. However, empirical data from Shandong Province from 1981 to 2014 suggested that environmental pollution worsens as the proportion of tertiary industries increases, and the relationship between the two factors follows a quadratic upward curve [50]. Therefore, local conditions should be taken into account when evaluating and analyzing O_3 contamination levels in a given region.

Values of 0.194 and 0.126 for the effect of per capita consumption expenditure and the number of industrial enterprises on the O_3 concentration, respectively, indicated a certain level of influence on the O3 concentration, but this influence is relatively weak. The R&D full-time equivalent of industrial enterprises above the designated size was an indicator of the level of scientific and technological development, with the interpretation of O_3 concentration standing at 0.182. However, the R&D full-time equivalent of industrial enterprises above a specified size emerged as the top economic factor affecting $PM_{2.5}$ concentration [13]. Due to the seesaw effect between $PM_{2.5}$ and O_3 treatment, summer $PM_{2.5}$ concentrations have decreased by approximately 40% in some areas of China over the past five years, leading to a corresponding decrease in heterogeneous absorption of HO_2 free radicals by aerosols but an increase in O_3 generation rates [13,16]. Currently, the total amount of major air pollutants in the YRD has exceeded its inflection point, and regional development is undergoing a period of environmental and economic enhancement while also experiencing coordinated development. Therefore, more effective measures were required to enhance the collaborative management of $PM_{2.5}$ and O_3 in order to promote the continuous improvement of air quality.

3.3. Interaction Detection Results

The Q-statistics results for the interaction effects resulting from the superposition of the eight driving factors are depicted in Figure 3. Clearly, the variability in O_3 concentration was an outcome of a combination of multiple factors, which were consistent with the principle of synergistic effects that jointly affect O_3 concentration. The interaction between urbanization, economic development, the ecological environment, and the level of technological development had a close impact on the O_3 concentration in the YRD region. Compared with the individual factors, the combined effect of any two factors showed a more significant effect on the variability in O_3 concentration.

The results of the interaction detection indicated that most of the interaction factors exhibited high values (>0.7), which dramatically enhances the explanatory power of the O_3 concentration. For instance, the interaction between per capita GDP and the proportion of tertiary industry was 0.916, and the combined effect of the proportion of tertiary industry and the urbanization rate was 0.851. The interaction between the proportion of tertiary industry and forest coverage was 0.912. It could be deduced that these three sets of factors could account for more than 80% of the variations in O_3 concentration. The R&D full-time equivalent and other economic factors were in the range of 0.46 to 0.93, indicating a close relationship between science and technology and socio-economic development, with science and technology involved in all aspects of the economy. As shown in Figure 3, the interaction was considerably enhanced between forest coverage and all types of economic factors (0.826~0.93). Particularly, the interaction between forest coverage and actual use of foreign investment was 0.904 and 0.912 for the proportion of tertiary industry, reflecting the strong connection between environment, science, and technology and socio-economic development. The remarkable interplay between any two factors demonstrated that imposing uniformity in all cases was not a viable approach for long-term environmental governance and that a comprehensive administration of the environment was required to govern O_3 in YRD.

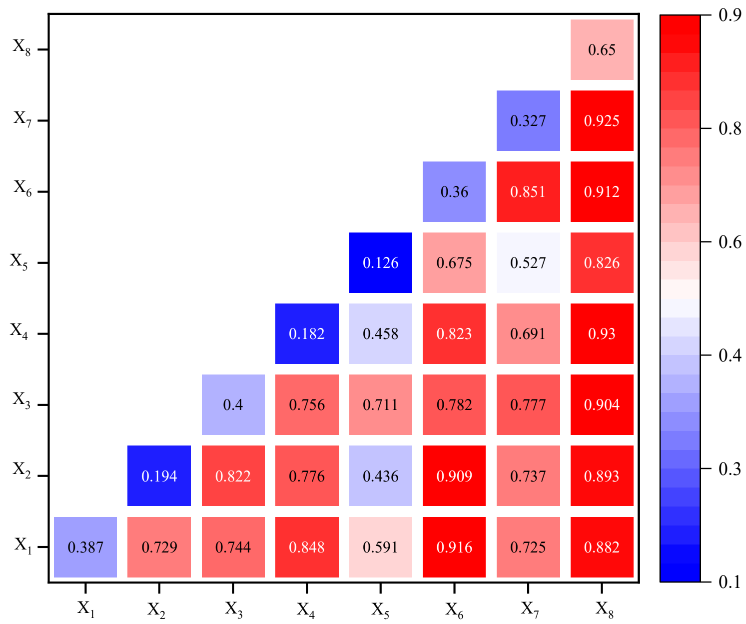

Figure 3. Interaction between economic and environmental factors.

4. Conclusions and Policy Implications

4.1. Conclusions

During our study, we focused on the impact of economic and environmental factors on O_3 concentration in the Yangtze River Delta region. Based on the results of the factor analysis, we identified the primary economic and environmental factors that contribute to O_3 concentration. A quantitative analysis was performed to determine their relation to O_3 concentration as well as their interaction mechanisms, enhancing our understanding of these relations and facilitating more targeted measurements of atmospheric conservation.

Among all factors, forest coverage stood out as the main one, playing a crucial role in atmospheric O_3 concentration. In terms of economic factors, the actual use of foreign investment has been demonstrated to have the highest explanatory power for environmental O_3 concentration, with per capita GDP serving as the secondary explanatory factor, followed by the proportion of tertiary industry and urbanization rate. The effect of per capita consumption expenditure and R&D full-time equivalent at industrial enterprises above a designated size was relatively low, and a minimum economic impact factor was found on full-time equivalent research and development (R&D) at industrial enterprises above a specified size. In addition, a positive impact was found between the actual use of foreign investment and the regional O_3 concentration, while others exhibited negative effects. The results of the interaction analysis revealed that the combined effect of any two factors has a more pronounced effect on the variation of O_3 concentration compared with their individual effects, especially when considering forest coverage and all types of economic factors, indicating that a comprehensive environmental administration is required to govern O_3 in the YRD.

4.2. Policy Recommendations

It has been shown that forest cover, actual foreign investment, GDP per capita, and the proportion of tertiary industries are the main economic factors affecting O_3 pollution in the Yangtze River Delta. Based on these findings, the following policy recommendations are proposed:

First, it is imperative to enhance foreign investment in strengthening measures to safeguard the atmospheric O_3 layer. Over the past 30 years, China has diligently adhered to the Montreal Protocol on Substances that Deplete the Ozone Layer and successfully eliminated a staggering 504,000 tons of O_3-depleting substances (ODS). However, there is still a lack of targeted countermeasures and strategies to address the environmental impact of O_3 emissions from foreign-funded enterprises. To mitigate the pollution impact of FDI, it is necessary to exercise strict control over the environmental access system while strengthening oversight of foreign investors transferring O_3-depleting substances through investments. In addition, to harmonize economic and environmental development and foster a favorable business environment for foreign investment, environmental pioneers and role models of multinational corporations in the control of O_3 pollution should be recommended, and environmental protection information needs to be widely spread to raise environmental awareness among the public.

Second, the implementation of comprehensive measures remains crucial to effectively controlling O_3 pollution. Due to the complex generation mechanism and significant temporal and spatial variability of O_3 contamination, comprehensive, differentiated, and refined measures should be implemented in the prevention and control of O_3 contamination to firmly avoid simplified and one-size-fits-all treatment approaches. The monitoring and governance system for O_3 pollution should be making improvements. Besides, it requires insisting on promoting the pivotal role of scientific research in the process of O_3 governance and collaborating with research institutions, universities, and large enterprises to enhance their research and the superiority and potentiality of development. Furthermore, the YRD region should strengthen the end of terminal processing, establish a comprehensive O_3 pollution governance system, and systematize the management of research on the generation mechanism.

Third, it is crucial to increase forest coverage in the YRD region, especially in the northern part. The implementation of land greening can effectively mitigate carbon emissions, enhance oxygen production, purify the air by reducing toxic and harmful gases, as well as radioactive substances, and contribute to the conservation and improvement of the ecological environment. Therefore, continuous improvement of forest coverage, increasing the richness of forest resources, and promoting regional balance of nature are long-term measures for the YRD to control O_3 pollution and promote integrated development of the ecological environment.

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