Pol. J. Environ. Stud. Vol. 32, No. 3 (2023), 2819-2831
DOI: *10.15244/pjoes/161670* ONLINE PUBLICATION DATE: 2023-04-06

Original Research

Spatial Spillover Effect of Pollution under Heterogeneous Environmental Regulations in the Perspective of Hidden Economy

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Received: 2 January 2023
Accepted: 25 February 2023

Abstract

The hidden economy, as an important source of environmental pollution, can have a significant impact on environmental regulation, but it has not received much attention as an indicator of institutional weakness. Therefore, this study took the Yangtze River Economic Belt (YREB) as the research object and used the MIMIC model and entropy method to measure the hidden economic scale and environmental pollution index of its 112 cities from 2011 to 2020, respectively. We applied the spatial Durbin model to analyze the effect of heterogeneous environmental regulation (formal and informal environmental regulation) and hidden economies on pollution. It is found that: (1) the average hidden economic scale of YREB from 2011 to 2020 was between 13.15% and 14.30% and showed a slow upward trend. (2) Environmental pollution in the YREB had obvious spatial clustering characteristics, with high pollution clustering areas mainly in Chongqing in the upper reaches and Hubei, Anhui, and Jiangsu in the middle and lower reaches, while low pollution clustering areas were mainly in Yunnan and Sichuan in the upper reaches. (3) Formal environmental regulation reduced pollution directly, and on the other hand exacerbated it through interaction with the hidden economy. Overall, an environmental regulation's net effect depended on the hidden economic scale. Informal environmental regulation effectively reduced local hidden economic activity and was an effective mean to govern the hidden economy and pollution. Accordingly, the government should formulate appropriate laws and regulations to guide the legal part of the hidden economy to gradually shift to the official economy, and at the same time adopt a diversified environmental protection strategy to jointly combat pollution in the YREB.

Keywords: environmental regulation, hidden economy, environmental pollution, Yangtze River Economic Belt, MIMIC model

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Introduction

After the opening up and reform, the Chinese economy has attained rapid and sustained growth and achieved great success. However, the crude economic development model, which relies excessively on resources, the environment, and factor inputs, has also brought about serious environmental pollution problems. In response to these problems, the government has issued a series of policies and laws, and regulations, and has strengthened its environmental management efforts, which have achieved great success, but the results of the management still fall short of expectations. In the context of regional integration, spatial spillover effects have become an important factor in regional studies as cities become more connected to each other. The spatial agglomeration and spillover effects of environmental pollution further make it more difficult for the government to combat them. In addition, the hidden economy, an important manifestation of institutional weakness, can also affect the governance outcome of environmental regulation. There was a relatively large scale of hidden economic activity in China. Based on data from China's fourth economic census (2018), the revised GDP for 2018 increased in total and magnitude by 189.72 billion CNY (Chinese Yuan) and 2.1% respectively compared to the original statistics. To some extent, this suggests that certain hidden economic activities are completely outside of statistics. As the hidden economy often includes a variety of illegal economic activities, its participants seek to avoid government regulation, which may also weaken the effect of environmental regulation to some extent.

The Yangtze River Economic Belt (YREB) has the longest depth, the widest coverage, and the greatest impact in China. The rapid development of the YREB since the 21st century has been accompanied by increasingly prominent environmental pollution problems. The Yangtze River Protection Law, which has been officially implemented in 2021, also proposes to strengthen environmental protection with more stringent measures and higher standards. Despite China's strict environmental regulation policies, however, as shown in the China Statistical Yearbook (2021), we found that the YREB still produced over 40% as much sewage, ammonia nitrogen, and sulfur dioxide emissions as the whole country. How to achieve green development of the YREB has become a widespread concern in academic circles. Using YREB as a case for research, this study focused on several issues: What are the effects of pollution caused by different types of environmental regulations? How do they relate to each other after considering the hidden economy? And whether there are spatial spillover effects of environmental pollution.

Literature Review

Environmental issues have always been the focus of academic research, and the examination of the relationship between the hidden economy, environmental regulation, and pollution has attracted the attention of an increasing number of scholars, with existing research focusing on the following three areas.

Firstly, the studies related to environmental regulation and pollution. The economist Pigou [1] was one of the first scholars to propose the idea of environmental taxation. He argued that "governments use macro-taxation to regulate environmental pollution". Much of the current research has concentrated on three areas: types of environmental regulations, their effectiveness, and their impact on technological innovation [2, 3]. In the studies of environmental regulation types, the classification varies between scholars. Pargal [4] was the first scholar to divide them into formal and informal. Kong [5] classified formal environmental regulation into market-incentive and command-and-control. Zhang and Yan [6] empirically analyzed the effects of these two types of regulation on technological innovation based on different research subjects. Turken [7] argued that command-and-control environmental regulation motivates enterprises to change their technology and in turn reduce pollution emissions. There is a debate between the "Porter hypothesis" and the "constraint hypothesis" regarding how environmental regulation affects technological innovation [8]. With the "constraint hypothesis", Huang and Ma [9] used the variable coefficient and mediating effects models to find that environmental regulations in growing resource cities were not conducive to technological upgrading. Some scholars based on the "Porter hypothesis" have argued that strong environmental regulation could improve their market competitiveness by promoting enterprises' technological innovation while reducing environmental damage [10-12]. However, Sinn [13] presented the 'green paradox', arguing that severe environmental regulation under certain conditions does not promote environmental protection. A study by Ramanathan et al. [14] showed that enterprises' choices varied widely and were uncertain when faced with strict regulations or market incentives that could be profit-seeking.

Secondly, the studies about the hidden economy and environmental pollution. The hidden economy, also called the informal economy, underground economy, or black economy refers to any illegal economic activity that evades government taxation or regulation and the income generated from it [15]. The three methods of measuring the hidden economy are direct [16], indirect [17], and modeling [18]. In addition to research on how to calculate the hidden economic scale, numerous scholars have studied its impact from different perspectives. Adizov [19] argued that the hidden economy can breed corruption and harm the investment climate and economic security of the region in which it is located. Chen and Sun [20] pointed out that the grey competition characteristic of the hidden economy reduced the level of regional innovation, while there was regional heterogeneity in this influence. Some scholars have found a positive correlation between pollution and the hidden economy from different perspectives. Biswas [21] concluded that the hidden economy exacerbates pollution. Elgin et al. [22] revealed that the effects of pollution caused by the hidden economy were first facilitated and then inhibited, showing an inverted "U" shape.

Thirdly, studies related to the interaction of environmental regulation and the hidden economy on the impact of environmental pollution. The hidden economy may diminish environmental regulation's effectiveness, so it is often seen as an important indicator of weakening the intensity of policy implementation [23, 24]. Han and Kou [25] argued that increased intensity of environmental regulation would only reduce superficial formal economic polluting behavior and would have no effect on or even amplify emissions from the hidden sector of the economy. Elgin and Mazhar [26] validated the relationship between the three using more than 100 countries' panel data and showed the effectiveness of environmental regulation in reducing pollution, but also in promoting the growth of the hidden economic scale.

There are still relatively few existing studies that combine the three elements of heterogeneous environmental regulation, the hidden economy, and pollution. In the few relevant studies, scholars have failed to consider the possible presence of the spatial effects of environmental pollution. Environmental pollution is characterized by spatial correlation, and its management has shifted from controlling local pollution problems to joint regional prevention and control, making its management policies have a spatially linked effect. Taking 112 cities in YREB as an example, we applied the Multiple Indicators Multiple Causes (MIMIC) model to measure the hidden economic scale in each city. Subsequently, a spatial Durbin model was constructed for examining the impact of formal and informal environmental regulations on pollution, in addition to exploring the effect of the hidden economy, to expect to provide efficient ways to combat the hidden economy and pollution.

Research Data and Methodology

Overview on the Study Area and Data Collection

The YREB is an essential economic corridor for China, with remarkable ecological status, strong comprehensive strength, and huge development potential. In China's development strategy, it plays an important role. It is tied by the Yangtze River, spanning China's three geographical ladders and three economic zones in the east, center, and west (Fig. 1), including nine provinces (Guizhou, Yunnan, Sichuan, Anhui, Hunan, Hubei, Jiangxi, Zhejiang, and Jiangsu) and two municipalities (Chongqing and Shanghai), covering a total area of around 2.0523 million KM^2, or 21.4% of the country. According to the China Statistical Yearbook (2021), we found in 2020 the YREB had a population and GDP of 606.07 million people and 47.158 trillion CNY respectively, accounting for 42.9% and 46.7% of the country, making it an essential driver for Chinese economic development during the new period. It includes 11 province-level administrative units with a total of 130 cities. In this study, 18 cities with incomplete data were excluded, and 112 cities were finally selected as the study unit, which was divided into the lower, middle, and upper reaches according to the Yangtze River Economic Belt Ecological and Environmental Protection Planning (2017).

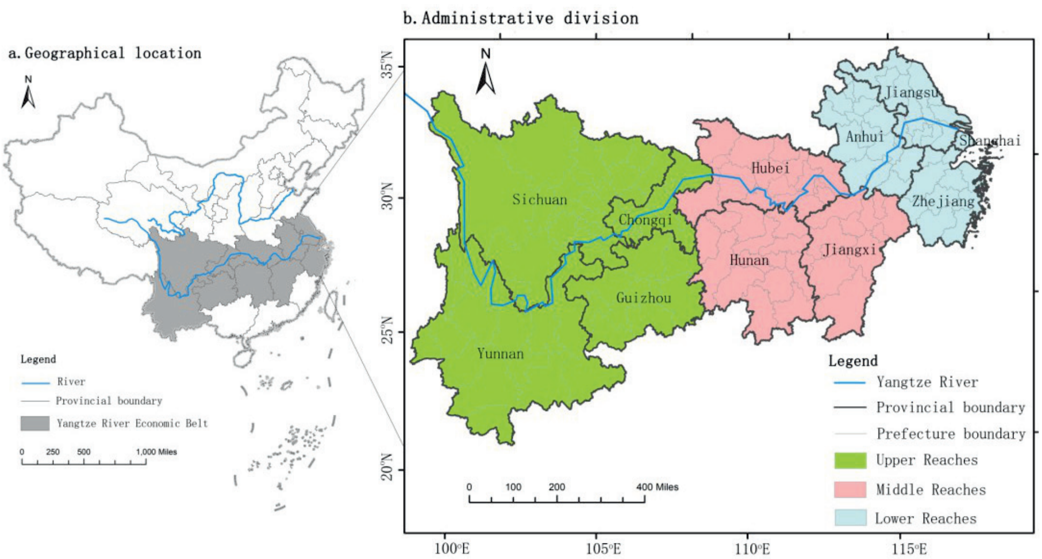

Fig. 1. Geographical location and administrative division of the YREB.

The upper reaches include 35 cities in 4 province-level administrative units of Sichuan, Chongqing, Guizhou, and Yunnan; the middle reaches include 36 cities in 3 provinces of Jiangxi, Hunan, and Hubei; and the lower reaches include 4 province-level administrative units of Jiangsu, Zhejiang, Shanghai, and Anhui, totaling 41 cities.

As an important industrial corridor and city-and-town concentrated area in China, the YREB's continuous high-emission production and lifestyle, high-intensity development and construction, high-density population layout, and backward environmental management patterns have caused it to suffer from increasingly serious problems such as ecological functions degradation and environmental quality deterioration. However, most existing environmental pollution studies in China focused on eastern regions and pollution-sensitive cities, and relatively little research has been conducted on the Yangtze River watershed. Therefore, taking it as an object of study has important implications for the harmonious economic and environmental development of the whole watershed.

There are three major categories of data used in this study. The first category is pollution and environmental regulation data. The environmental pollution data includes industrial wastewater emissions, industrial so2 emissions, and industrial smoke (dust) emissions for each city. With public concern over air pollution, cities have set up air monitoring stations and published the city's Air Quality Index (AQI) together with concentrations of different pollutants in real time. Data on industrial smoke (dust) emissions and industrial SO2 emissions were obtained from the Air Monitoring Station of the Chinese Ministry of Environment (http://www.cnemc.cn/) and industrial wastewater emissions from the China City Statistical Yearbook. Data on formal environmental regulation was obtained from the government work reports of individual cities. Informal environmental regulation was reflected by the degree of public concern about the environment, which is expressed by the Baidu Index, an indicator obtained from the official website of the Baidu Index (https://index.baidu.com). Search for the keyword "environmental pollution" on the Baidu index website to get the specific index.

The second category is socio-economic statistics, including indicators such as year-end population, the output value of the secondary industry, the number of green patent authorizations, the number of enterprises, the amount of foreign investment, and GDP. These indicators were derived through the 2012-2021 China City Statistical Yearbook, the 2012-2021 China County Statistical Yearbook, and the State Statistical Bureau of the People's Republic of China (http://www.stats.gov.cn/). The urban land area and the number of industrial enterprises above the designated size were supplemented through provincial statistical yearbooks.

The third category is the administrative division vector data, which was derived from the National Catalogue Service For Geographic Information (http://www.webmap.cn). Administrative divisions were consolidated and unified according to 2020, and for areas that changed, they were counted according to the adjusted divisions. Taking into account data completeness and continuity, the panel data of 112 cities in the YREB were finally chosen for analysis.

The explained variable in this study is the environmental pollution index (*ep*), and the core explanatory variables include the scale of hidden economic (*se*) and the intensity of formal and informal environmental regulation (*fer*, *ier*). Industrial structure (*stur*), technological innovation capacity (*inno*), population density (*pop*), and trade openness (*open*) can also affect a city's level of environmental pollution, so they were included as control variables. We used the number of green patent authorizations as an indication of technological innovation capacity. The enhancement of technology innovation capacity is conducive to the upgrading of production methods and clean environmentally friendly technologies, thus enhancing the efficiency of resource use, reducing pollutant emissions, and contributing to the improvement of regional environmental conditions. We used the year-end population to land area ratio to express population density. The more densely populated an area is, the more people are impacted by pollution and, as such, the more people participate in informal environmental regulation. This study used the proportion of secondary industry output in the total output of each city to express the industrial structure. We expressed the degree of trade openness in terms of the amount of foreign direct investment as a proportion of GDP. Within the background of economic globalization, an influx of FDI has contributed greatly to rapid economic development, while at the same time influencing the environment.

Methodology

Environmental Pollution Index Calculation

Environmental pollution index (*ep*). Drawing on studies related to environmental pollution measurement [27-31], this paper applied three indicators, industrial wastewater emissions, and industrial smoke (dust) emissions, industrial SO_2 emissions, to obtain the weights of emissions for 2011-2020 using the entropy value method. Then, the environmental pollution index for each city in the YREB was calculated using the weighted summation method with the following formula:

$$P_i = \sum_{j=1}^{3} Z_{ij} \times w_j \tag{1}$$

P_i is the environmental pollution index of the city *i*; w_j indicates the weight of variable *j*; Z_{ij} refers to the standardized value of variable *j* of the city *i*;.

Environmental Regulation Intensity Calculation

Formal environmental regulation (*fer*). There are currently no standardized criteria to measure formal environmental regulation, and the available indicators include the number of environmental administrative penalty cases [5], the removal rate of three industrial wastes [6], and a polluter treatment facility's annual operating costs [9]. These methods are indirect measures that do not adequately measure the intensity of environmental regulation. Drawing on Li et al. [32], this study used the frequency of words in municipal government work reports related to "environmental protection" as a proxy variable (e.g., energy saving and emission reduction, green ecology, low carbon, clean, new energy, ecological environment, environmental protection), with the following formula.

$$fer_i = \frac{env_{it}}{tot_{it}} \times \frac{abv_{it}}{ent_{it}} \tag{2}$$

Where: fer_i is the intensity of formal environmental regulation in the city *i*. Higher values indicate the greater intensity of formal environmental regulation. env_{it} is the word frequency of "environmental protection" in the government work report of the city *i* in year *t*. tot_{it} is the frequency of all words in the government work report of the city *i* in year *t*. abv_{it} is the number of industrial enterprises above designated size in the city *i* in year *t*. *entit* is the number of all enterprises in the city *i* in year *t*.

Informal environmental regulation (*ier*). Drawing on Xu's [33] study, we searched for the keyword "environmental pollution" in the Baidu index and obtained the index for each city from 2011 to 2020. The annual mean was then selected to be a proxy variable to account for a city's informal environmental regulation. This indicator's value reflects the extent to which people are concerned about pollution issues, and a higher value is associated with a greater intensity of informal environmental regulation.

Hidden Economic Scale Calculation

The hidden economic scale (*se*). The MIMIC model has been widely used in its calculation [34-36]. Drawing on the study of Yang and Sun [37], this study selected tax burden, unemployment rate, per capita disposable income, and employment rate as the cause variables, and the labor participation rate and GDP per capita as the outcome variables to construct a MIMIC model for calculating the regional hidden economic scale. The two components, measurement, and structural models form the MIMIC model (Equations (3) and (4)).

$$y = \gamma(se) + \mu \tag{3}$$

$$se = \beta x + \varepsilon \tag{4}$$

Where *se* is the latent variable, representing the unobservable hidden economy. *y* represents the possible outcomes and impacts of the hidden economy, namely the indicator variable; while γ represents the coefficient of the impact of the hidden economy on each indicator variable and μ represents the error term. *x* denotes a group of observable cause variables affecting the hidden economy, ε denotes the random disturbance term, and β denotes the amount of change in the latent variable per unit change in the cause variable.

Calculate the covariance matrix for each variable to better suit the analytical requirements of the MIMIC model for panel data. The specific conversion method is:

$$x_{jit} = \left(x_{jit} - \bar{x}_{jit}\right) \; y_{jit} = \left(y_{jit} - \bar{y}_{jit}\right) \tag{5}$$

j denotes the number of variables, *j* = 1, 2,..., 6; *i* denotes the city, *i* = 1, 2,..., 112; and *t* denotes the year.

Drawing on the study findings of Yang and Sun [37] and He et al. [38], the hidden economy index of each city in the YREB for the period 2011-2020 was calculated using 2011 as the base year.

$$seco_{i,t} = seco_{i,2011}\left(\frac{\eta_{it}}{\eta_{i,2011}}\right) \tag{6}$$

Where $seco_{it}$ denotes the hidden economic scale as a proportion of GDP in year *t* of the region *i*; $seco_{it,2011}$ represents the base year, that is, the hidden economy as a percentage of official GDP in 2011; ηit is the calculated initial hidden economic scale.

Calculation of Spatial Spillover Effects

There is a need to take into account its spatial spillover effect as environmental pollution in neighboring areas can also affect each other and a spatial autocorrelation test is required. Our study calculated the spatial autocorrelation by Moran's *I* index.

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\left(x_i - \bar{x}\right)\left(x_j - \bar{x}\right)}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij} \sum_{i=1}^{n}\left(x_j - \bar{x}\right)^2} \tag{7}$$

Where *n* refers to the total number of area samples; $\bar{x}$ indicates the average value of environmental quality of all areas in the same year, and x_i, x_j, indicate the environmental quality of area *i* and area *j* respectively, and $W = (w_{ij})n \times n$ is the spatial weight matrix, using geographical distance weight, that is, the reciprocal of distance as the spatial weight, indicating that the influence of one area on another area decreases with the increase of distance, the specific calculation can be realized by ArcGIS software.

Moran's *I* index reflected each environmental quality indicator's spatial agglomeration characteristics. For indicators with strong spatial correlation, the spatial Durbin model (SDM) was brought in for measuring the spatial spillover effect of pollution:

$$ep_{it} = \alpha_0 + \alpha_1 fer_{it} + \alpha_2 ier_{it} + \alpha_3 se_{it} + \alpha_4 fer_{it} \cdot se_{it} + \alpha_5 ier_{it} \cdot se_{it} + \alpha_6 x_{it} + \rho W ep_{it} + \alpha W fer_{it} + \beta W ier_{it} + \lambda W se_{it} + \gamma W fer_{it} \cdot se_{it} + \tau W ier_{it} \cdot se_{it} + \delta_i + \mu_t + \varepsilon_{it} \quad (8)$$

ep_{it} denotes the pollution degree; fer_{it} and ier_{it} denote the intensity of formal and informal environmental regulation respectively. se_{it} denotes the scale of the hidden economy; $fer_{it} \cdot se_{it}$ and $ier_{it} \cdot se_{it}$ are the interaction terms between informal and formal environmental regulation and the hidden economy, reflecting the indirect impact of environmental regulation on pollution by means of the hidden economy; W denotes the spatial weight matrix; x_{it} is the control variables; ρ is the spatial lag coefficient; μ_t denotes the time fixed effect, δ_i denotes the individual fixed effect, and ε_{it} denotes the random error term.

Results

The Spatial-Temporal Variations

The environmental pollution index for the YREB between 2011 and 2020 followed an upward and then downward trend (Fig. 2a). By region, pollution was more serious at the lower reaches, the second-most serious at the middle reaches, and relatively lighter at the upper reaches, largely because there were more heavy chemical enterprises in the lower reaches, which caused greater pressure on the environment. With the Chinese government's call for "no major development, common protection" and the introduction of environmental policies in various regions, pollution in the lower and middle reaches has improved slightly, and the role of environmental regulation became evident recently.

The average hidden economic scale of the YREB grew from 13.15% in 2011 to 14.3% in 2020 (Fig. 2b). In terms of region, the lower reaches had the largest scale of hidden economies, between 13.64% and 15.47%, while the middle and lower reaches had a relatively small scale of hidden economies, varying from 12.99% to 13.73% and 12.67% to 13.52% respectively. With the YREB being elevated to a national strategy, international economic cooperation and trade exchanges have driven up its overall economic level, and the volume of hidden economic activities has gradually increased, which, together with the inadequate market supervision system brought about by the transformation of the economic system, has further contributed to the spread of underground economic activities. Especially in the lower reaches, rising consumption levels, improved transport systems, and the frequent movement of people and trade have provided opportunities for underground economic activity, hence the relatively high scale of its hidden economy.

There was an upward trend in the strength of informal and formal environmental regulation (Fig. 2c, Fig. 2d). This showed the growing importance attached to environmental issues by both officials and the public. Viewed by region, the intensity of environmental regulation showed a more pronounced pattern of being highest in the lower reaches, second highest in the middle reaches, and least in the upper reaches. This is due to the lower reaches are mostly located in the developed eastern regions, where environmental regulations start from a high level and are more stringent in comparison, while the middle and upper reaches are growing in intensity but at a relatively small range.

The Spatial Spillover Effect of Environmental Pollution

Environmental pollution in an area not only arises from local production activities but is also influenced by the surrounding area. To gauge the spatial agglomeration of pollution, we used the GeoDa 9.0 spatial data analysis software to check the spatial autocorrelation of the pollution indices among 112 cities in the YREB and obtained the Moran's *I* index and its test values (Fig. 3). Moran's *I* index for 2011-2020 varied between 0.101 and 0.317 and passed the 5% significance test in all years. It showed a positive spatial autocorrelation of the YREB's pollution, presenting spatial clustering characteristics.

We further drew LISA agglomeration maps of environmental pollution for 2011, 2014, 2017, and 2020 to reflect the spatial variability in the agglomeration of pollution (Fig. 4). Judging from the spatial clustering, the high pollution agglomeration areas were mostly located in Chongqing, Hubei, Anhui, and Jiangsu, while those of low pollution were largely located in Yunnan and Sichuan. Over time, the scope of low-value pollution agglomeration gradually expanded from the upper reaches of southwestern Yunnan to northern and central Sichuan. The scope of the high-value pollution agglomeration area has gradually narrowed to the south of Hubei in the middle reaches and Anhui and southern Jiangsu in the lower reaches.

The spatial autocorrelation of environmental pollution exists and therefore spatial factors are included in the scope of this paper. In Table 1, the outcomes of the Wald test and LR test indicated a superiority of the SDM over both the spatial autoregressive model (SAR) and spatial error model (SEM). The SDM was chosen to examine the impact of formal and informal environmental regulation and the hidden economy on

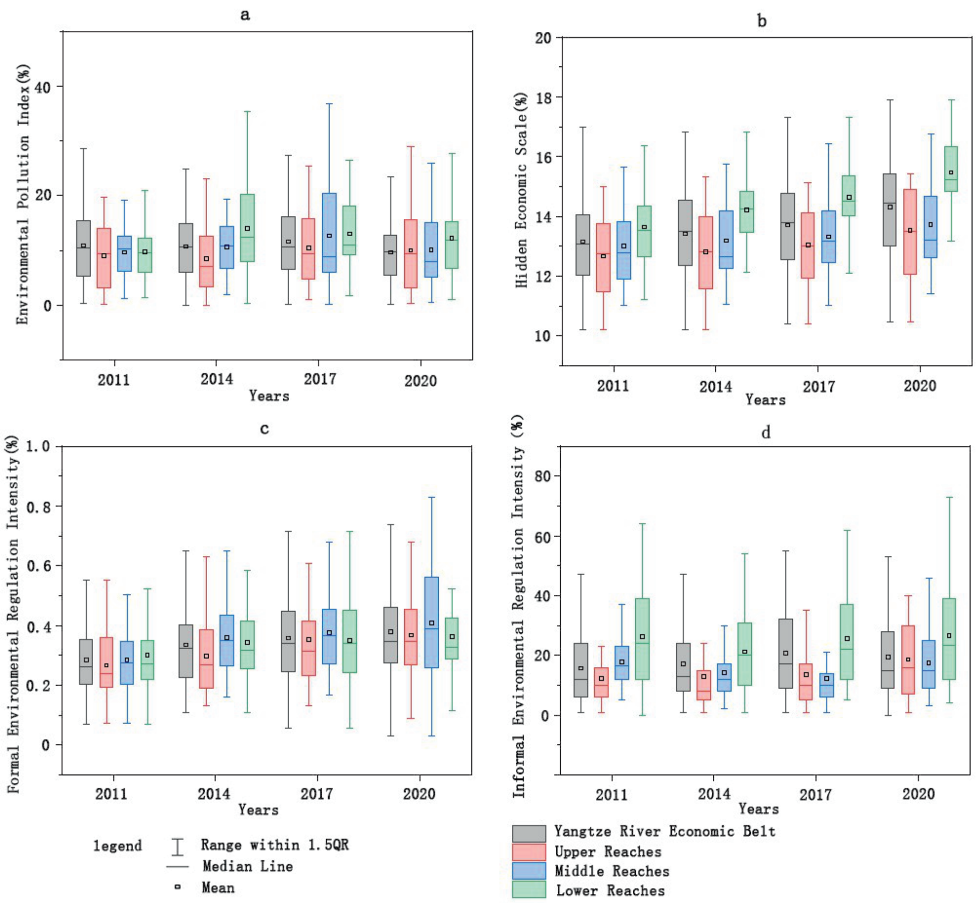

Fig. 2. Box plots of changes in the hidden economic scale, environmental regulation intensity, and environmental pollution index in the YREB in 2011, 2014, 2017 and 2020.

pollution. Taking into account possible individual or time-varying unobserved effects, this study further divided the SDM models into time fixed effects models, individual fixed effects models, as well as two-way fixed effects models. This study decomposed each explanatory variable's impact on the explained variable by indirect effect, direct effect, and gross effect based on the partial differential method, and Table 2 showed the spatial Durbin regression results. From Table 1, the Log-likelihood and R-squared for the individual fixed effects model were all significantly above those for time fixed effects and two-way fixed effects models. When considered together, the results of the individual fixed effects model were the primary focus of this study.

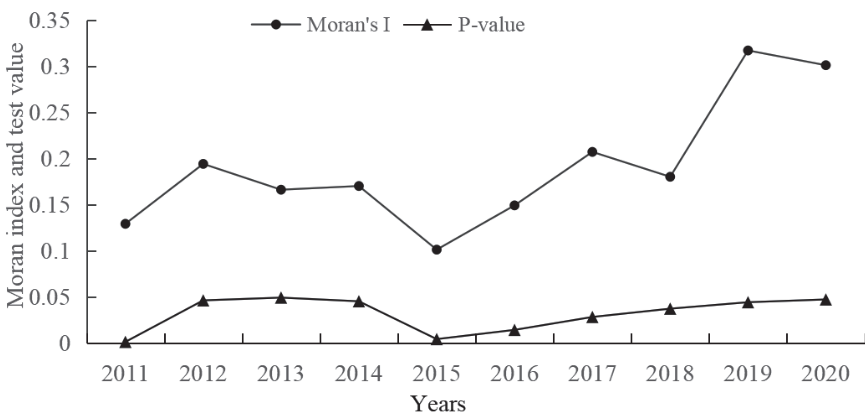

Fig. 3. Moran's I and test p-value for environmental pollution in the YREB, 2011-2020.

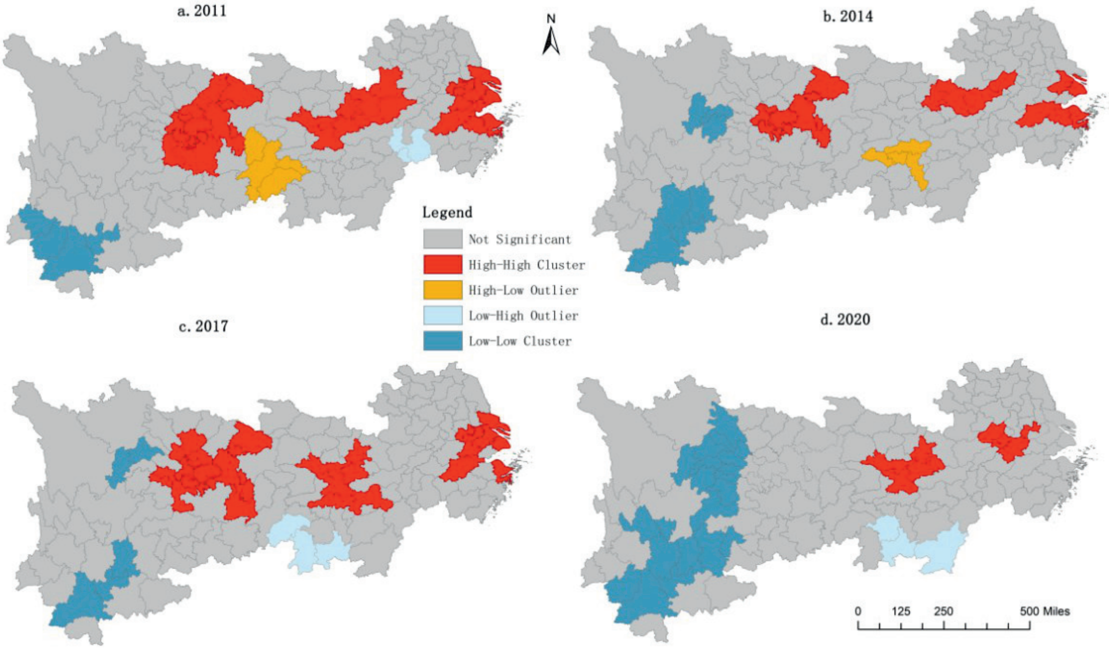

Fig. 4. LISA agglomeration maps of environmental pollution in the YREB in 2011, 2014, 2017 and 2020.

Significantly negative indirect and direct effects of formal environmental regulation (*fer*) indicated that in the absence of the hidden economy, government environmental regulations were effective in mitigating pollution and improving environmental quality in cities. An increase in a city's level of formal environmental regulation can significantly reduce pollution levels in neighboring cities. The reason for this is that, on the one hand, neighboring cities are mostly under the jurisdiction of the same provincial unit and have convergence in policy formulation and implementation. In the face of severe environmental pressure, neighboring cities may adopt more similar protection policies, resulting in a convergence of their formal environmental regulation levels. Meanwhile, owing to the presence of the knowledge spillover, green production technology can quickly flow between neighboring cities, enabling them to ride on the "free ride" of improved environmental quality. In addition, the mutual learning behavior that exists between neighboring cities is an important reason for this spatial spillover effect.

The indirect and direct effects of the interaction term between formal environmental regulation and the hidden economy (*fer·se*) were both positive, indicating their interaction has a positive contribution to pollution. The above findings suggested that the expansion of the hidden economic scale can distort the policy effects of environmental regulation, which means harsh policies can increase the cost of emissions for enterprises, prompting them to shift their polluting behavior to the hidden sector of the economy and thus expand pollution.

The direct effect of informal environmental regulation (*ier*) was significantly positive, probably because the hidden economy was smaller or the pollution problem was not serious enough for the public's environmental protection demands to have sufficient influence on highly polluting enterprises. The direct effect of informal environmental regulation and

Table 1. Results of spatial econometric model test.

Test index	Test method	Statistical value	*p*-value
LM test	LM test no spatial lag	3.1643	0.0653
	LM test no spatial error	82.1472	0.0000
Robust LM test	Robust LM test no spatial lag	8.0653	0.0027
	Robust LM test no spatial error	91.3251	0.0000
LR test	LR test spatial lag	25.2700	0.0001
	LR test spatial error	67.0700	0.0000
Wald test	Wald test spatial lag	25.4500	0.0001
	Wald test spatial error	51.5700	0.0000

the hidden economy interaction term was significantly negative, indicating that the pollution problems associated with a certain scale of hidden economic activity can stir up public dissatisfaction with that production activity. The people's continued interest in environmental issues has broken the invisibility of the hidden economy. The people are promoting continuous improvement in environmental quality by putting pressure on the government. The indirect effect of the interaction between informal environmental regulation and the hidden economy was not significant, suggesting that public environmental governance has an "island effect" and does not have a strong governance impact around the surrounding area.

The coefficient of the hidden economy (*er*) was found to be significantly positive, indicating that its presence will aggravate the pollution of the YREB. Hidden economic activities usually use production technologies that have been phased out or are pollution-intensive, and there is no shortage of unlicensed and polluting production enterprises such as black coal kilns, black workshops, and dangerous chemical plants, which inevitably exacerbate pollution.

For the other control variables, the technological innovation capability variable regression coefficient was significantly negative, indicating that it was negatively correlated with pollution, meaning that its improvement could significantly improve environmental quality. The premise of environmental technology upgrading is to vigorously improve technological innovation, which can reduce and monitor the emission of pollutants in the production process and thus better improve ecological and environmental issues. Population density showed a clear positive correlation. As urbanization progresses, the population has concentrated in large cities, which will inevitably increase the consumption of urban resources, while at the same time, the pollutant emissions from an overly dense population will also have an impact on the environment. The coefficient on the industrial structure was significantly positive. Industrial production activities will bring about resource consumption and pollutant emissions, which cause environmental problems when their emissions exceed the capacity of the environment. The gross effects of trade openness, direct, and indirect were all significantly positive, suggesting that the "pollution paradise" hypothesis was also applicable to the YREB.

Regional Heterogeneity Analysis

The YREB straddles three different areas of China: West, East, and Central. The regression of the SDM model results in Table 3 showed that the interaction term between formal environmental regulation and the hidden economy was significantly positive in the lower and upper reaches. The reason for this finding may be that the lower reaches are mostly developed cities on the eastern coast, which bear the burden of being the first to achieve economic transformation and high-quality development. Following the increasing attention of local governments to environmental damage, strict environmental regulations have led some highly polluting small and middle scale enterprises to expand the scale of their hidden economic activities to circumvent policy constraints. The growing scale of the hidden economy and its spatial spillover has led to increased pollution in neighboring cities. The upper reaches of the YREB are remote and have underdeveloped transportation systems. As a result, it made government regulation of corporate pollution emissions difficult, hidden economic activities gradually expanded, and environmental policy implementation was less effective. The interactive effect of the hidden economy with formal environmental regulation in the middle reaches was not significant. The middle reaches have to some extent taken over the energy-consuming and highly polluting industries from the developed lower reaches. The high costs and risks of these industries result in high barriers to entry for hidden capital, therefore the pollution effect of the hidden economy on the environment was not significant.

The interactive effect of informal environmental regulation and the hidden economy was not significant in either the lower or middle reaches. Currently, there were a series of problems such as non-transparent environmental information of enterprises, low level of public participation in environmental decision-making, and non-standardized individual environmental behavior, resulting in low public supervision and binding power on enterprises' pollution behavior. The interactive effect of informal environmental regulation and the hidden economy showed significantly negative impacts in the upper reaches. The reason for this may be that in recent years, as the nation has increased its efforts to protect the Yangtze River source ecology, the public, as the main body of environmental participation, has responded to the national call to actively expose the pollution practices of enterprises and to some extent combat hidden economic activities.

For the other control variables, technological innovation capacity was significantly negative in the lower reaches, but not significant in the middle and upper reaches. Green production and treatment technologies in the lower reaches are being developed and promoted and have become an essential driver for building an ecologically civilized society. However, insufficient technological innovation capacity and lagging technology diffusion in the middle and upper reaches have to some extent been detrimental to ecological improvement. The coefficient on population density was notably positive in the lower and middle reaches. This was caused by the high population density and urbanization levels in the lower and middle reaches, where the concentration of the population increases resource consumption and pollutant emissions, thus exacerbating pollution at all levels of socio-economic activity. However, the upper reaches were more sparsely populated and had an insignificant impact on pollution.

Table 2. Spatial Durbin regression results of formal and informal environmental regulations.

	(1) individual fixed effect			(2) time fixed effect			(3) two-way fixed effect		
	Direct effect	Indirect effect	Gross effect	Direct effect	Indirect effect	Gross effect	Direct effect	Indirect effect	Gross effect
fer	-1.1326***	-4.3472**	-5.4798**	4.4649***	29.2553***	33.7202***	-0.0637	1.7375	1.6738
	(-2.6522)	(-2.1952)	(-2.5546)	(3.1384)	(3.8652)	(3.3074)	(-0.1962)	(1.3763)	(0.9421)
ier	0.0168**	0.0191	0.0359	0.0146	-0.3872**	-0.3726*	0.0142*	0.0032	0.0174
	(1.9762)	(0.4982)	(0.7641)	(0.3872)	(-2.3923)	(-1.6421)	(1.8624)	(0.2758)	(0.7035)
se	0.0334***	0.1834***	0.2168***	0.0168	0.0355	0.0523	0.0504***	0.1750***	0.2254***
	(6.9712)	(3.4771)	(5.0521)	(0.6862)	(0.6492)	(0.3762)	(9.8721)	(5.4024)	(6.5461)
fer·se	0.1567***	0.4352**	0.5919**	-0.1573**	-1.7652***	-1.9225***	0.0487	-0.1863	-0.1376
	(2.8692)	(2.1073)	(2.6972)	(-2.0863)	(-3.8764)	(-3.2642)	(0.5873)	(-1.0971)	(-0.8652)
ier·se	-0.0003*	-0.0035	-0.0038	-0.0005	0.0112*	0.0107	-0.0002	-0.0009	-0.0011
	(-2.3468)	(-0.8341)	(-0.9321)	(-0.0247)	(1.4213)	(1.0367)	(-1.8422)	(-0.2689)	(-0.5625)
inno	-0.0781***	-0.1432**	-0.2213**	0.1387***	0.3972***	0.5359***	-0.1071***	-0.2862***	-0.3933***
	(-2.8732)	(-1.9762)	(-2.1656)	(5.1256)	(3.6702)	(3.1464)	(-5.1346)	(-3.1578)	(-3.9754)
pop	1.1358***	4.8532***	5.9890***	3.1353***	13.1453***	16.2806***	0.5321***	2.2248*	2.7569**
	(3.8743)	(3.1334)	(3.4231)	(3.0053)	(3.4853)	(2.6532)	(2.9732)	(1.8421)	(2.0862)
stru	0.1072***	0.2966***	0.4038***	-0.1733*	-0.2175	-0.3908	0.0572**	0.1478**	0.2050**
	(4.8756)	(3.3982)	(4.1863)	(-1.9832)	(-1.2981)	(-1.6584)	(2.5832)	(2.0973)	(2.1922)
open	0.0468***	0.1682***	0.2150***	-0.0148*	-0.0742	-0.0890	0.0179***	0.0468***	0.0647***
	(6.3671)	(5.1468)	(5.6833)	(-1.9872)	(-1.2876)	(-1.6621)	(4.0861)	(1.7752)	(3.8652)
ρ			0.6486***			0.6577***			0.5752***
R-squared			0.4683			0.1322			0.2761
Log-likelihood			561.5637			-106.1746			588.4282

Note: The z-statistic for each coefficient is shown in parentheses, *, ** and *** denote 10%, 5% and 1% significance levels respectively. The symbols in Table 3 have the same meaning as in Table 2.

The industrial structure was significantly positive in the lower and middle reaches, but not in the upper reaches, which was associated with the relatively high degree of industrialization in the lower and middle reaches. As for trade openness, it was notably positive in the lower reaches, but not in the lower and middle reaches. The lower reaches have a well-developed market economy and a large volume of import and export trade, and the production, import, and export of great quantities of primary goods have a certain impact on the local environment.

Discussion

This study incorporated both hidden economic and environmental regulations into the research on pollution. This is an important experiment and provides a new perspective for understanding pollution governance in the new era. The study found that formal environmental regulation can significantly decrease pollution, which has similarities with the results of Guo and Chen [39]; informal environmental regulation can also alleviate pollution under the influence of the hidden economy. This indicated that environmental pressure from the public and the government was gradually becoming an important factor influencing the dynamics of pollution, which was in agreement with the results of the study by He et al. [38]. With the effect of online media messages, the significance of informal environmental regulation in the area of environmental governance is gradually increasing. However, due to problems such as information asymmetry and the lack of uniform environmental standards, the process of information fermentation on the internet has the potential for informal environmental regulation behavior that is blindly followed, and this is something that needs attention.

Table 3. Spatial Durbin regression results in upper, middle, and lower reaches.

	Upper reaches			Middle reaches			Lower reaches		
	Direct effect	Indirect effect	Gross effect	Direct effect	Indirect effect	Gross effect	Direct effect	Indirect effect	Gross effect
fer	-1.7746***	-1.9857*	-3.7603**	-0.3982	-0.7539	-1.1521	-3.0872***	-6.3852***	-9.4724***
	(-2.8362)	(-1.6733)	(-2.0934)	(-0.4872)	(-0.2175)	(-0.3143)	(-1.9862)	(-4.3982)	(-3.0523)
ier	0.0136**	0.0237	0.0373*	-0.0134	0.0682	0.0548	0.0059	-0.0083	-0.0024
	(2.0832)	(1.3822)	(1.5832)	(-0.5483)	(0.5532)	(0.1192)	(0.7524)	(-0.6942)	(-0.1211)
se	-0.0264***	-0.0673***	-0.0937***	-0.0782***	-0.1788**	-0.2570**	-0.0038	0.0543*	0.0505
	(-4.5372)	(-2.5663)	(-3.4825)	(-2.8732)	(-2.0762)	(-2.4734)	(-0.3872)	(1.2863)	(1.3822)
fer·se	0.0782***	0.1973**	0.2755**	0.0352	0.0386	0.0738	0.1672***	0.4932***	06604***
	(3.0182)	(2.4322)	(2.8732)	(0.4973)	(0.2332)	(0.3092)	(1.9873)	(4.1973)	(3.2533)
ier·se	-0.0008	-0.0041*	-0.0049*	0.0015	-0.0010	0.0005	-0.0003	0.0007	0.0004
	(-1.6432)	(-1.9553)	(-1.7528)	(0.6532)	(-0.5743)	(0.0731)	(-0.3463)	(0.6432)	(0.3743)
Inno	0.0257	0.0214	0.0471	0.0387	0.0490	0.0877	-0.1752***	-0.1382***	-0.3134***
	(0.6853)	(0.6183)	(0.6482)	(0.5497)	(0.5103)	(0.5198)	(-3.9722)	(-3.5382)	(-3.1447)
pop	0.0603*	0.3164**	0.3767**	0.1563***	0.2156*	0.3719**	0.0363	0.0432	0.0793
	(1.6321)	(2.3664)	(2.0242)	(2.8696)	(1.5852)	(2.3754)	(0.2256)	(0.2785)	(-0.1582)
stru	0.0287	0.0483	0.0770	0.1893***	0.1996***	0.3889***	0.0673**	0.0862*	0.1535*
	(1.7532)	(0.8622)	(1.2764)	(3.4899)	(2.4292)	(2.9632)	(2.1465)	(1.5859)	(1.7962)
open	-0.0734	-0.0532	-0.1266	-0.1972	-0.1852	-0.3824	0.0347**	0.0178*	0.0525**
	(-1.3728)	(-1.0492)	(-1.2772)	(-0.8632)	(-0.6329)	(-0.7732)	(2.3822)	(2.0719)	(2.1739)
ρ			0.5486***			0.6043***			0.5218***
R-squared			0.5476			0.5028			0.6973
Log-likelihood			213.5943			137.6136			175.2682

This study based on a city scale empirically analyzed the influence of pollution caused by heterogeneous environmental regulations and hidden economy, which could provide a reference basis for government environmental protection departments to formulate and improve differentiated management measures. Firstly, when formulating environmental regulations and emission standards, the government should take the pollution's spatial agglomeration characteristics and the phenomenon of "neighbors as neighbors" into consideration, implement joint prevention and control strategies, give full play to the spatial spillover effect of heterogeneous environmental regulations, and avoid falling into the "fighting alone" mode of scattered governance. Secondly, the government should adopt a diversified strategy of environmental governance. While attaching importance to formal environmental regulation, it must also play an informal environmental regulation role in combating pollution, improving the reporting and petition system, and encouraging public participation in the management of pollution problems. Thirdly, existing policies generally adopt a tough attitude towards hidden economic activities, such as "if found, punish severely", but the government's persistent suppression does not achieve the desired effect. Therefore, the government should formulate reasonable laws and regulations to guide the legal part of the hidden economy to gradually shift to the official sector, so that production activities can be carried out reasonably and legally.

Limited by the availability of data, this study only measured environmental regulation intensity from the Baidu index and the frequency of environmental words in government work reports. In future research, multiple data can be obtained through investigation, interviews, and big data for analysis, to more scientifically gauge the intensity of environmental regulations and refine their types. Environmental regulation, the hidden economy, and pollution are in a relationship that involves different stakeholders such as enterprises, the public, and the government. In the next research, we will select representative polluting industries to further analyze the inner mechanism of the interaction between different interest subjects and seek more effective ways of environmental governance.

Conclusions

We examined the links among heterogeneous environmental regulations, hidden economy, and pollution from a spatial spillover perspective using the spatial econometric model with a panel of 112 cities in the YREB for 2011-2020 as a sample. We have attempted to better dissect the mechanisms by which environmental regulation and hidden economic act on pollution, enriching to some extent the theory of sustainable development. The primary conclusions are as follows.

(1) From a hidden economic scale, the average value of the YREB ranged from 13.15% to 14.30% and showed a slow growth trend. On a regional basis, the lower reaches had the highest scale of hidden economies, the middle reaches the second and the upper reaches the smallest. Both formal and informal environmental regulation intensity exhibited a growing trend, indicating that both governments and the public were paying more attention to the environmental pollution problem. The pollution index of the YREB tended to increase and then decrease, with environmental problems easing and the effect of environmental regulation becoming apparent.

(2) Environmental pollution had significant spatial spillover effects. Spatial correlation coefficients for pollution were all significantly positive, suggesting obvious spatial characteristics. High-pollution agglomeration areas were mostly located in Chongqing in the upper reaches and Hubei, Anhui, and Jiangsu in the middle and lower reaches, while low-pollution agglomeration areas were mostly located in Yunnan and Sichuan in the upper reaches, showing a significant spatial convergence phenomenon and path-dependent characteristics in general. With a polarising tendency in regional pollution, the extent of the low-value pollution agglomeration area has progressively grown and the extent of the high-value pollution agglomeration area has gradually reduced over time.

(3) Government-led formal environmental regulation reduces pollution by disciplining highly polluting enterprises and reducing emissions of pollutants from the formal sector of the economy, but its coercive and strict nature leads to a shift in economic activity towards the hidden economy, which in turn increases the hidden economic scale and exacerbated pollution. Informal regulation has effectively curbed the spread of highly polluting hidden economic activities, becoming an important way to control the hidden economy and govern pollution. The interaction between formal environmental regulation and the hidden economy had a significantly positive effect on pollution in both lower and upper reaches. However, the interaction between informal environmental regulation and the hidden economy has shown a significantly negative influence on pollution in the upper reaches, acting as a disincentive to pollute the environment, but its effect on the lower and middle reaches was not significant.

(4) Technological innovation capacity had a significantly negative effect while the population density and industrial structure had a significantly positive effect on pollution. In addition, there was a significant positive effect of trade openness on pollution, suggesting that the “pollution sanctuary hypothesis” was still valid in the YREB.

Conflict of Interest

The authors declare no conflict of interest.

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