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## Article

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## Research paper

# Assessing the efficiency of China's environmental regulation on carbon emissions based on Tapio decoupling models and GMM models

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## ABSTRACT

This paper takes 30 provinces in China from 2004 to 2015 as research samples, using the Tapio decoupling models, differential GMM methods and peak forecasting models to analyze the effect of environmental regulation on carbon emissions, and subdividing the research sample from the regional and temporal dimensions to analyze the effectiveness of environmental regulations in different regions and at different time periods. The analysis results show that, with the advancement of environmental regulation, the dependence of China's economic growth on fossil energy has experienced a process from weak to strong and weak. There is a significant inverted U-shaped curve relationship between environmental regulation and CO<sub>2</sub> emissions and CO<sub>2</sub> emissions intensity. As the intensity of environmental regulation changes from weak to strong, the impact effect changes from “green paradox” effect to “back-forced reduction” effect. The effect of environmental regulation in the eastern region is better than that in the central and western regions. However, with the implementation of environmental regulation, the inverted U-shaped curve between environmental regulation and carbon emissions gradually becomes flat. The results of the peak forecast show that China has crossed the peak of CO<sub>2</sub> emissions intensity, but has not exceeded the peak of CO<sub>2</sub> emissions. By further optimizing environmental regulations, China may reach its CO<sub>2</sub> emissions peak by 2030. Overall, China's environmental regulations at the current stage can effectively curb carbon emissions and achieve the desired goals.

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## 1. Introduction

Since the implementation of reform and opening up, China has achieved remarkable economic growth. However, China's economic growth has a distinct dualistic nature. That is, agriculture subsidizes the industry. The share of GDP in the primary industry continued to fall from 27.7% in 1978 to 8.6% in 2016. The rapid growth of China's economy is highly dependent on the development of industry. However, the high growth of Chinese industry has obvious features which is high investment, high energy consumption, and high emission. The problem of environmental pollution and climate change that China is facing has become increasingly prominent under the background of rapid economic growth. To achieve sustainable economic growth and environmental protection, the Chinese government proposes to build a “beautiful China” target and integrate ecological civilization into economic, political, cultural, and social development to form the overall layout of sustainable development. At the same time, the

Chinese government promised that China's carbon dioxide emissions intensity in 2020 will be 40%–45% lower than that in 2005. To achieve the goal of building “beautiful China” and reducing carbon dioxide emissions, the Chinese government has successively introduced a series of environmental policies to limit and guide companies' carbon dioxide emissions practices, and correct the market mechanism's response to carbon dioxide emissions by implementing environmental regulation policies. However, some scholars have questioned the necessity and effectiveness of environmental regulation. Whether or not environmental regulation can reduce carbon emissions has not yet reached a consensus. It can be summarized into three perspectives: to begin with, based on neo-classical economic theory, related scholars put forward “restriction theory”, saying that environmental regulation will increase the production cost of enterprises, consume the innovation input of enterprises and cause “green paradox” effect, which is not conducive to reducing carbon emissions (Schou, 2002; Sinn, 2008). The second is the Porter Hypothesis. Porter and Van der Linde (1995) believes that proper environmental regulation can stimulate the “compensation for innovation” effect, which can not only make up for the “compliance costs” of the company, but also increase the productivity and productivity of the company.

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This means that environmental regulation can lead to the “back-forced reduction” effect. Finally, the impact of environmental regulation on carbon emissions is uncertain. China’s environmental regulations can reduce carbon emissions, that is, the “back-forced reduction” effect is established? Or accelerate carbon emissions, resulting in “green opinion” effect? Answering the above questions not only helps to accurately assess the effectiveness of China’s environmental regulations in reducing carbon emissions, but also has important practical significance for the formulation of China’s environmental regulatory policies.

## 2. Literature review

Regarding whether environmental regulation can reduce carbon emissions, there are three main points of view in academia. The first view is that environmental regulation cannot reduce carbon dioxide emissions, but will have the opposite result. Sinn (2008) put forward the concept of “green paradox” effect and believe that the policy measures to limit climate change will lead to accelerated exploitation of fossil energy and speed up Greenhouse Gas Emissions. Sinn (2008) further summarizes three possible mechanisms that lead to the “green paradox” effect: (1) incorrect carbon taxation; (2) policy measures to reduce fossil energy demand; (3) time lag between policy announcement and enforcement. Since then, there have been a lot of theoretical literature on the effects of carbon emissions management policies on global emissions. The main topics of concern include: whether the “green paradox” effect exists; the mechanism of the “green paradox” effect. Gerlagh (2011) and Smulders et al. (2012) analyzed the mechanism of “green paradox” effect, and stressed that the supply side’s response to environmental regulations has enabled energy owners to move forward and expedite energy depletion, leading to an increase in carbon dioxide emissions. Van der Werf and Di Maria (2012) research supports Sinn’s view that imperfect climate policies increase short-term carbon emissions, and in the long run, environmental regulation will decrease the net present value of future environment caused by climate change.

The second view is that environmental regulation can improve ecological efficiency, promote technological innovation in enterprises, and achieve the goal of energy conservation and emission reduction. Ren et al. (2018) used 30 Chinese provinces and cities as an analysis sample and found that an effective environmental regulation system is the key driving force for improving regional eco-efficiency. Shen et al. (2017) analyzed the geographical location of pollution-intensive enterprises in Guangdong Province from 2000 to 2013 and believed that environmental regulation can inhibit the formation of new pollution havens. Xie et al. (2017) studied the relationship between different regulatory instruments and “green” productivity. The conclusions support the Porter Hypothesis, that is, reasonable stringency of environmental regulations may enhance rather than lower industrial competitiveness. The reason is that environmental regulation can generate intra-firm knowledge spillovers, promote the technical efficiency of a certain department, and then transfer these enhancements to other units within their fleet (Galloway and Johnson, 2016).

The third view is that the effect of environmental regulation on carbon emissions is uncertain. Yuan and Xiang (2018) found that in the short term, environmental regulations can increase the green total factor productivity, while in the long-term, environmental regulations will squeeze out R&D input. Although energy use efficiency increases, labor productivity and green total factor productivity decrease. Wang and Shen (2016) and Zhang and Xu (2016) studied the relationship between environmental regulation and total factor productivity, and concluded that in different industries, the effect of environmental regulation on the total factors

differs. For technology-intensive industries, environmental regulation can increase total factor productivity. In labor-intensive industries, the role of environmental regulation is not significant. Guo et al. (2017) believe that environmental regulation can promote the improvement of regional green growth performance, but the positive correlation between the two is regulated by technological innovation. Only when environmental regulation can stimulate technological innovation, environmental regulation can achieve its expected goal.

Through sorting out the existing literature, we can see that research on the effect of environmental regulation on carbon emissions reduction has yielded rich research results, but there is still room for improvement in the existing research. To start with, the direction of the impact of environmental regulation on CO<sub>2</sub> emissions has not yet been fully agreed. The impact of environmental regulation on CO<sub>2</sub> emissions may be positive or negative. Next, existing research suggests that the functional form of environmental regulation on carbon emissions is a monotonous linear form, but the impact of environmental regulation may be non-linear. The reason is that, on the one hand, appropriate environmental regulations can make up for the company’s “compliance costs” (Porter and Van der Linde, 1995). It can also increase the productivity and competitiveness of enterprises (Galloway and Johnson, 2016), which in turn will lead to advances in production technology and upgrades in environmental protection technologies to reduce carbon emissions. On the other hand, environmental regulation raises the cost of corporate pollution control, squeezes out R&D investment from enterprises, and reduces the production efficiency of enterprises, which is not conducive to the improvement of carbon emissions reduction and environmental governance (Yuan and Xiang, 2018). Furthermore, existing research suggests that the impact of environmental regulation on carbon emissions is fixed. However, with the implementation of environmental regulation policies, the improvement of the ecological environment makes the effect of environmental regulation intensity at the same level different. Fourth, due to the differences in the level of economic development and carbon emissions in different regions of China, the impact of environmental regulation varies in different regions. However, the existing studies on China’s environmental regulation ignore China’s regional differences. The insufficiency of existing research makes the evaluation of the effectiveness of environmental regulation inaccurate.

The main contributions of the paper are as follows. To begin with, we use data from 30 provinces in the Chinese mainland from 2004 to 2015 as research samples. In order to more accurately assess the effectiveness of China’s regional environmental regulatory policies, we further divide the research samples into eastern, central and western regions, and divides the study window interval of the sample into 2004–2007, 2008–2011 and 2012–2015 to reflect the specific national conditions and distinctive stage characteristics of China’s economic development. Then we use the Tapio decoupling model to examine the relationship between economic growth and the carbon dioxide emissions, per capita carbon dioxide emissions, and carbon dioxide emission intensity, to find individual differences and commonalities in each province, and to grasp the overall development trend of China’s carbon dioxide emissions. Then, this paper uses the differential GMM method to test the nonlinear relationship between environmental regulation and CO<sub>2</sub> emissions and CO<sub>2</sub> emissions intensity. In addition, we further analyze the effects of environmental regulations in different periods and regions, and evaluate the effectiveness of environmental regulation from horizontal and vertical dimensions. Third, this paper uses peak forecasting method to predict the peak value and peak time of CO<sub>2</sub> emissions and CO<sub>2</sub> emissions intensity in China. Then we analyze the impact of current environmental regulation policies on the future peak value and peak time of CO<sub>2</sub>

**Table 1**  
CO<sub>2</sub> emissions factors.

Energy	China's energy average low calorific		Carbon emissions factor (IPCC, 2006)		Carbon oxidation factor	Energy conversion factor for standard coal		Estimated carbon emissions factor	
	Value	Unit	Value	Unit		Value	Unit	Value	Unit
Coal	Bituminous coal		25.8		0.99	0.7143	kg standard coal/kg	2.763	kg/kg standard coal
	Anthracite coal	20 908	26.8						
	Weighted average	KJ/kg	26.0	kg/1 000 000 kJ					
Crude oil	41 816		20.0		1	1.4286		2.145	
Natural gas	38 931	KJ/m <sup>3</sup>	15.3		1	1.3300	kg standard coal/m <sup>3</sup>	1.642	

emissions and CO<sub>2</sub> emissions intensity to examine the effectiveness of environmental regulation. The structure of the latter part of the article is as follows: Section 3 is the data description and model construction. Section 4 analysis the empirical results. Section 5 provides the research conclusions and policy recommendations.

### 3. Data description and model construction

#### 3.1. Carbon dioxide emissions estimation and data sources

Carbon dioxide emissions mainly come from the burning of fossil fuels and the production processes of cement, lime, and steel. According to the World Bank report, fossil fuel combustion accounts for more than 70% of total carbon dioxide emissions, and China's energy supply is mainly based on heavily polluted coal fuels. Coal consumption accounts for 85% of total energy consumption. Therefore, the calculation of CO<sub>2</sub> emissions in the world is mostly based on fossil energy consumption. This paper mainly uses the primary energy sources such as coal, crude oil, and natural gas, which have large energy consumption, to calculate CO<sub>2</sub> emissions of 30 provinces in China. The calculation method of CO<sub>2</sub> emissions is provided by the Intergovernmental Panel on Climate Change IPCC (2006), and the specific calculation formula is shown in model (1):

$$TCO_2 = \sum_{i=1}^3 CO_{2,i} = \sum_{i=1}^3 E_i \times NCV_i \times CEF_i \times COF_i \times \left( \frac{44}{12} \right) \quad (1)$$

TCO<sub>2</sub> is the sum of carbon dioxide emissions, CO<sub>2,i</sub> is the estimated CO<sub>2</sub> emissions of three primary energy sources, *i* represents the three primary energy sources, E<sub>*i*</sub> represents energy consumption. NCV<sub>*i*</sub> is the net heating value of the three primary energy which is provided by the China Energy Statistical Yearbook of 2007. CEF<sub>*i*</sub> represents the carbon emissions factor provided by IPCC (2006). There is no direct supply of the coal's emissions factor, but China's consumption of coal has been dominated by bituminous coal, accounting for 75%–80%, and anthracite accounts for about 20%, and the coal classification and the consumption of various types of coal have not changed substantially over the years. Therefore, this paper uses the weighted average method (weight of bituminous coal is 80% and weight of anthracite coal is 20%) to calculate the carbon emissions factor of coal. Carbon emissions factors for bituminous and anthracite coal are provided by IPCC (2006). COF<sub>*i*</sub> is carbon oxidation factor (coal is set at 0.99, crude oil and natural gas are 1). 44 and 12 are the molecular weight of carbon dioxide and carbon. Since the energy consumption units used by the IPCC (2006) and the China Energy Statistical Yearbook are not uniform, the energy units used in this paper will be uniformly converted into standard coal which is used to measure China's energy consumption (Chen, 2009). The China Energy Statistical Yearbook of 2007 provides the conversion factors which conversions three energy to standard coal. The reference factors used in the CO<sub>2</sub> estimation process and the estimated CO<sub>2</sub> emissions factors for coal, crude oil, and natural gas are shown in Table 1.

The data used in this paper is drawing from the China Statistical Yearbook, China Regional Economic Statistical Yearbook and China

Energy Statistical Yearbook from 2004 to 2015. Due to the lack of CO<sub>2</sub> emissions and energy consumption statistics, the sample did not include Tibetan.

#### 3.2. Tapio decoupling model specification

The Tapio decoupling model and its indicators can reflect the relationship between economic growth and carbon dioxide emissions, and help to grasp the development trend of regional carbon emissions. Tapio (2005) subdivides the decoupling state into eight states according to the decoupling elastic value. The eight decoupling states are strong decoupling, weak decoupling, weak negative decoupling, strong negative decoupling, expansive negative decoupling, expansive coupling, recessive decoupling, recessive coupling. Strong decoupling refers to sustained economic growth, but the carbon dioxide emissions are negative growth. It shows a negative relationship between carbon dioxide emissions and economic growth, and the decoupling elasticity value is between  $-\infty$  and 0. Weak decoupling refers to stable economic growth. Although carbon dioxide emissions are growing, its growth rate is smaller than the growth rate of GDP, and the decoupling elasticity value is between 0 and 0.8. Weak negative decoupling refers to the negative growth of the economy and the negative growth of carbon emissions. However, the rate of carbon emissions deceleration is smaller than that of economic growth, and the decoupling elasticity value range from 0 to 0.8; strong negative decoupling refers to negative economic growth and carbon emissions is still tend to rise. The decoupling elasticity value is between  $-\infty$  and 0; Expansive coupling means that carbon emissions increase at roughly the same rate as economic growth. The relationship between them is linear, and the decoupling elasticity value is in the range of 0.8 to 1.2. Expansive negative decoupling means that the carbon emissions growth rate is higher than the economic growth rate, and the decoupling elasticity value is generally greater than 1.2; Recessive coupling refers to the negative growth of the economy, and the carbon emissions show the same proportion of negative growth. The elasticity value is between 0.8 and 1.2; Recessive decoupling represents a negative growth in both economic and carbon emissions, but the reduction in carbon dioxide emissions is faster than the economic contraction. The elasticity value is greater than 1.2. The average annual GDP growth rate of the 30 provinces from 2004 to 2015 is higher than 7%. Therefore, there are no recessive decoupling, weak negative decoupling, strong negative decoupling, recessive coupling. There may only be four states: strong decoupling, weak decoupling, expansive coupling, or expansive negative decoupling.

In order to comprehensively reflect the decoupling between carbon emissions and economic growth and comprehensively analyze the trend of carbon emissions in China, this study uses the three indicators of total carbon dioxide emissions, per capita carbon emissions, and carbon intensity to measure the decoupling elasticity value with economic growth. The specific formula for calculating the decoupling elasticity value between the three indicators and economic growth is shown in models (2), (3) and (4):

$$e(TCO_2GDP) = \% \Delta TCO_2 / \% \Delta GDP \quad (2)$$

**Table 2**  
The state of decoupling and decoupling elasticity value.

Decoupling state	Carbon emissions growth	Economic growth	Decoupling elasticity value
Strong decoupling	–	+	$(-\infty, 0)$
Weak decoupling	+	+	$(0, 0.8)$
Expansive coupling	+	+	$(0.8, 1.2)$
Expansive negative decoupling	+	+	$\geq 1.2$
Recessive decoupling	–	–	$\geq 1.2$
Weak negative decoupling	–	–	$(0, 0.8)$
Strong negative decoupling	+	–	$(-\infty, 0)$
Recessive coupling	–	–	$(0.8, 1.2)$

$$e(\text{PCO}_2\text{GDP}) = \% \Delta \text{PCO}_2 / \% \Delta \text{GDP} \quad (3)$$

$$e(\text{GCO}_2\text{GDP}) = \% \Delta \text{GCO}_2 / \% \Delta \text{GDP} \quad (4)$$

$\% \Delta \text{TCO}_2$ ,  $\% \Delta \text{PCO}_2$  and  $\% \Delta \text{GCO}_2$  represents the growth in total carbon emissions, per capita carbon emissions, and carbon intensity.  $\% \Delta \text{GDP}$  indicates the growth of GDP from the base period to the final period. This paper sets 2004 as the base period and adjusts the nominal GDP of each province to the real GDP at a constant price. In order to reflect China's overall carbon emissions trend, this paper divides 2004–2015 into three periods: 2004–2007, 2008–2011, and 2012–2015 to reflect the distinctive stage characteristics.

### 3.3. Modeling of the impact of environmental regulation on carbon emissions

Conceptually, environmental regulation is an important category of government social regulation. It means that because of the unsustainability of fossil energy and the external diseconomy of pollution caused by industrial activities, the government passes the pollution permit, administrative penalties, and levying environment-concentration-tax to manufacturers, to achieve sustainable environmental and economic development. Testa et al. (2011) divides environmental regulation into three categories according to its degree of enforcement: direct regulation (standards, command and control), economic tools (taxes and fees, tradable emission permits, etc.) and “soft” measures (resource industry agreement, environmental certification programs, etc.). Therefore, the purpose of the government's environmental regulation policy is to protect the environment. It is expected that the effect of environmental regulation on carbon emissions will be a positive reduction. For example, the government imposes carbon taxes, energy taxes, etc. on producers and users of fossil energy which will increase their production costs and environmental costs and reduce energy demand, and thus help to reduce carbon emissions. During the “Twelfth Five-Year Plan” period in China, the Chinese government implemented a subsidy policy on clean energy such as wind power and photovoltaic power generation, and encouraged the use of renewable energy sources to reduce the demand for fossil energy. Obviously, both the taxation of fossil fuels and the subsidies for clean energy are all started from reducing the demand for fossil fuels in order to achieve the purpose of emission reduction. However, as Sinn (2008) put it, “good intentions do not always lead to good behavior”. The “green paradox” effect may also be the result of environmental regulation, which is rooted in the dynamic response of the supply side. Fossil energy owners expect environmental regulations to become more stringent, thereby moving the mining path forward over the entire time horizon, leading to the current decline in fossil fuel prices. In the short term, the demand for cheaper fossil fuels will increase. This will be followed by an increase in short-term carbon emissions. That means the “green opinion” effect may be more significant.

Fig. 1 shows the impact path of environmental regulation on carbon emissions. Environmental regulation affects CO<sub>2</sub> emissions through both the supply side and the demand side of fossil energy. The “back-forced reduction” effect and the “green paradox” effect coexist, which means that the impact of environmental regulation on carbon emissions is not monotonously linear. However, with the different intensity of environmental regulation, the “back-forced reduction” effect and the “green paradox” effect are shifting. When the intensity of environmental regulation is weak, the “green paradox” effect is more significant. when the intensity reaches a certain “threshold”, the effect of environmental regulation will be changed from the “green paradox” effect to the “back-forced reduction” effect, that is, the impact of environmental regulation on carbon emissions is inverted U-shaped.

Through analysis, we can see that there is a U-shaped curve relationship between environmental regulation and carbon emissions rather than a monotonous linear relationship. So this paper adds environmental regulation ( $Er$ ) and the square of environmental regulation ( $Er^2$ ) to examine its non-linear effects. At the same time, the natural logarithm of per capita real GDP ( $Y$ ) and its squared term ( $Y^2$ ) is introduced into the model, taking into account the existence of an environmental Kuznets curve (EKC) hypothesis between carbon emissions and per capita income (Grossman and Krueger, 1991). In addition, due to inertia or partial adjustment, there may be a lag effect in CO<sub>2</sub> emissions, and introducing lag terms can better control lag factors. Based on the above considerations, an dynamic panel model (5) is constructed to measure the impact of environmental regulation on carbon emissions:

$$\ln C_{i,t} = \beta_0 + \beta_1 \ln C_{i,t-1} + \beta_2 \ln Er_{i,t} + \beta_3 (\ln Er_{i,t})^2 + \beta_4 \ln Y_{i,t} + \beta_5 (\ln Y_{i,t})^2 + \xi X_{i,t} + \delta_i + \varepsilon_{i,t} \quad (5)$$

where the  $i$  and  $t$  represent provinces and years respectively;  $C_{i,t}$  refers to carbon emissions ( $Ce$ ) and carbon emissions intensity ( $Cei$ ) of each province;  $\delta_i$  represents environmental regulation, and it reflects persistent inter-provincial differences;  $\varepsilon_{i,t}$  refers to the specific heterogeneous effects, and assuming it is normally distributed;  $X_{i,t}$  is the other control variable that may affect carbon emissions, including energy consumption structure ( $Ens$ ), industry structure ( $Ins$ ), technology level ( $Tel$ ), foreign direct investment ( $FDI$ ), and population scale ( $Peo$ ).

Environmental regulation ( $Er$ ) is the core explanatory variable of this paper. At present, the relevant data of this variable is difficult to obtain and the data quality is relatively weak. Considering the relative perfectness of indicators and the availability of data, this paper refers to the method of measuring environmental regulation by Zhang et al. (2011) and uses the ratio of investment in industrial pollution control to the industrial added value as an indicator of environmental regulation. The amount of investment in industrial pollution treatment reflects the government's wishes and reflects the government's efforts and determination in environmental management. It thus represents the strength of actual environmental regulation. Generally, the stricter the environmental regulation in a region is, the greater the amount it is for environmental governance. That is, higher intensity of environmental regulation leads to more investment in pollution control. The energy consumption structure ( $Ens$ ) in the control variables is represented by the proportion of coal consumption in total energy consumption. The industrial structure ( $ns$ ) is measured by the proportion of the output value of the secondary industry to the regional GDP. Technology level ( $Tel$ ) is measured by the ratio of R&D expenditure to real GDP in each province. Foreign direct investment ( $FDI$ ) uses the ratio of actual use of foreign direct investment to real GDP to measure. The population scale ( $Peo$ ) is the total population of each province. Table 3 is a descriptive statistical analysis of all variables.

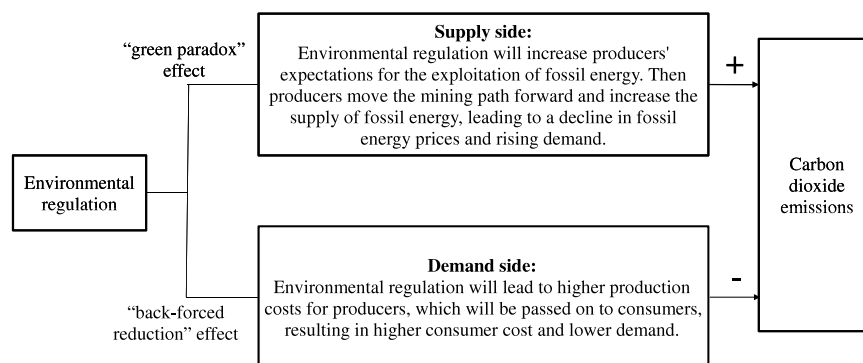


Fig. 1. Impact path of environmental regulation on carbon emissions.

Table 3  
Descriptive statistical analysis of variables.

Variable	Definition	Average value	Standard deviation	Min	Max
<i>Ce</i>	The logarithm of carbon dioxide emissions amount	4.34	0.34	3.06	5.04
<i>Cei</i>	The logarithm of the ratio of total carbon dioxide emissions amount to real GDP	13.25	4.83	8.91	15.07
<i>Y</i>	The logarithm of per capita real GDP	4.43	0.29	3.63	5.81
<i>Er</i>	The ratio of investment in industrial pollution control to the industrial added value	6.04	6.86	3.39	10.27
<i>Ens</i>	The proportion of coal consumption in total energy consumption	63.09	31.81	39.61	91.03
<i>Ins</i>	The proportion of the output value of the secondary industry to the regional real GDP	47.13	7.72	19.74	59.05
<i>Tel</i>	The ratio of R&D expenditure to real GDP	3.23	1.68	1.97	7.33
<i>FDI</i>	The ratio of actual use of foreign direct investment to real GDP	2.54	2.11	1.18	6.96
<i>Peo</i>	The logarithm of the total population	5.89	1.17	4.61	7.72

## 4. Results and analysis

### 4.1. Decoupling status analysis

According to the models (2), (3) and (4), we can calculate the decoupling elastic values between the three carbon emission indicators and economic growth separately, and determine the decoupling state of different provinces by referring to Table 2. Figs. 2–4 show the decoupling status of 30 provinces measured from the three indicators between 2004 and 2015. The three sub-graphs in each figure represent the decoupling status of total carbon dioxide emissions, per capita carbon emissions, and carbon intensity. The results show that during the period from 2004 to 2007, the economic growth of 30 provinces was significantly positively correlated with carbon emissions. The decoupling elasticity value of 14 provinces which is calculated by the total carbon emissions index exceeds 1.2. The decoupling elasticity indicates that the 14 provinces are in a state of expansive negative decoupling. The decoupling status of period 1 shows that China's economic growth was highly dependent on fossil fuels during 2004–2007, and it is a mode of extensive economic growth. At this stage, the implementation of the Chinese government's environmental regulation policy is not firm enough. Data from the “China Statistical Yearbook” shows that environmental protection investment even experienced negative growth in 2005.

During the period from 2008 to 2011, China's environmental regulation policy and the environmental protection investment has been continuously improved. The ratio of environmental protection investment to GDP has increased by 23.1% compared with the previous period 1. The mode of economic growth in China gradually returns to rationality. The economy of each province is still at a high growth stage, but the growth of carbon emissions has slowed down, and the number of provinces which are in a state of expansive negative decoupling has decreased from 14 to 2. China's economic development mode has gradually shifted to a relatively intensive type.

During the period from 2012 to 2015, the Chinese government has promoted environmental protection to a national strategic position, focusing on the governance of air, water, and soil pollution, and has been promoting pollution control. For example, in 2014, the Ministry of Environmental Protection issued the “Interim Measures of the MEP Interview”, and for the first time conducted an “interview” on environmental issues with the principal government officials of 13 cities and supervised the implementation of environmental regulation policies. Affected by this, the relationship between China's economic growth and carbon emissions is generally decoupled. The decoupling elasticity value of total carbon emissions, the decoupling elasticity value of per capita carbon emissions, and the decoupling elasticity value of carbon emissions intensity are all very small. Economic growth has a small role in promoting carbon emissions. There are 13 provinces in which the three indicators have been decoupled at the same time. The economic growth patterns of 13 provinces are in a resource-saving and environment-friendly manner. Only Ningxia and Xinjiang are in a state of expansive negative decoupling.

Overall, China's economic growth mode has changed from relatively intensive to intensive. The decoupling of the three periods shows that the mode of economic growth in 30 provinces has gradually shifted from extensive to intensive. However, the impact of environmental regulation on carbon emissions cannot be examined only through the decoupling status of economic growth and carbon emissions. It cannot be quantitatively evaluated about the impact of environmental regulation on the transformation of China's sustainable development approach. Therefore, we further examine the impact of environmental regulation on carbon emissions through the analysis of regression results.

### 4.2. Analysis of regression results

During the sample period, the process of industrialization and urbanization in China accelerated its development. At the same time, the environmental issues became more and more prominent. The central and local governments attached more importance to the concept of sustainable development. For example, in the evaluation of the performance of government officials, the indicators of “scientific development” and “ecological civilization” were

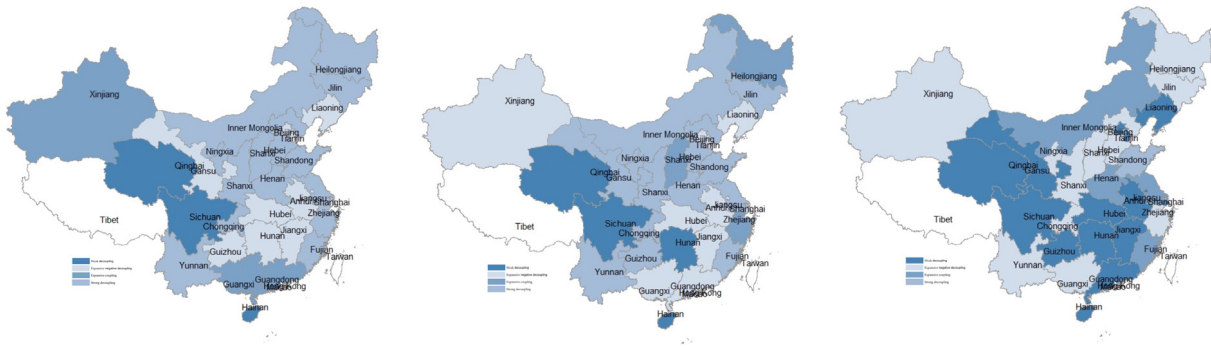


Fig. 2. 2004–2007 decoupling status.



Fig. 3. 2008–2011 decoupling status.

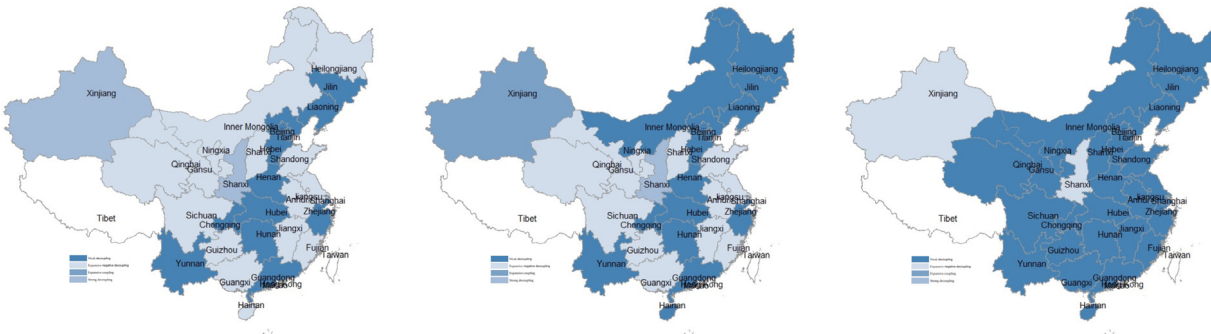


Fig. 4. 2012–2015 decoupling status.

added, and these have prompted local governments to increase their investment in environmental protection and strengthen the enforcement of environmental regulations. Therefore, at different stages, there are differences in the impact of environmental regulation on carbon emissions. In addition, because 30 provinces have significant differences in their functional orientation, resource endowments, energy consumption structure, and industrial structure across the country, the huge differences in various factors will also affect the relationship between environmental regulation and carbon emissions. Therefore, this paper first estimates the entire sample of 30 provinces, and then separately estimates the three different periods and the eastern, central, and western regions to analyze the changes in the impact of environmental regulations in different periods and regions. Since the first-order lagged term of the dependent variable is introduced as independent variable in the econometric model, the sample data is converted into dynamic panel data. In this paper, the differential GMM estimation method is used for regression analysis. In order to eliminate the individual heterogeneity that does not change with time, the differential transformation method is used to convert the model (5) into the

model (6).

$$\begin{aligned} \ln C_{i,t} - \ln C_{i,t-1} = & \beta_1(\ln C_{i,t-1} - \ln C_{i,t-2}) + \beta_2(\ln Er_{i,t} - \ln Er_{i,t-1}) \\ & + \beta_3[(\ln Er_{i,t})^2 - (\ln Er_{i,t-1})^2] \\ & + \beta_4(\ln Y_{i,t} - \ln Y_{i,t-1}) + \beta_5[(\ln Y_{i,t})^2 \\ & - (\ln Y_{i,t-1})^2] + \xi(X_{i,t} - X_{i,t-1}) \\ & + (\varepsilon_{i,t} - \varepsilon_{i,t-1}) \end{aligned} \quad (6)$$

In order to overcome the endogenous problem of all independent variables and the correlation between the residual term and dependent variable,  $\{\ln C_{i,0}, \ln C_{i,1}, \dots, \ln C_{i,t-2}\}$  is used as the instrumental variables. At the same time, in order to test the effectiveness of instrumental variables, Hansen test and Arellano–Bond AR (2) test were used to determine the validity of instrument variables and model settings.

#### 4.2.1. Full sample regression results

Table 4 shows the full-sample regression results of the dependent variables for total carbon dioxide emissions and carbon

emissions intensity. The results of Arellano–Bond AR (2) test show that there is no second-order autocorrelation in the residual sequence. The Hansen test results show that the null hypothesis of the validity of instrumental variables cannot be rejected. Models 1–3 are the estimates of the relationship between control variables, environmental regulation, and CO2 emissions and CO2 emissions intensity. From the regression results of Model 1–3, the real GDP is significantly positively correlated with CO2 emissions and CO2 emissions intensity, while the square of per capita real GDP is significantly negatively correlated with CO2 emissions and CO2 emissions intensity. There is a significant inverted U-shaped curve relationship between per capita real GDP and carbon emissions, indicating the existence of environmental Kuznets Curve. In addition, all the models show that the population scale has a significant role in promoting carbon emissions. Rapid population growth leads to a rapid increase in energy consumption, which poses a severe challenge to the carrying capacity of resources and the environment. Furthermore, the energy consumption structure is positively correlated with carbon emissions at the 1% level of significance. Because coal's carbon emissions are 1.2 times that of oil and 1.6 times that of natural gas, the positive impact of energy consumption structure on carbon emissions reflects China's current energy endowment of coal-rich, oil-poor, and gas-poor. China's energy consumption is dominated by coal, which will hinder the realization of China's carbon emissions reduction targets for a long time. The industry structure and carbon emissions are positively correlated at the 1% level of significance, reflecting that the increase in the proportion of heavy industries will increase carbon emissions. The technology level is negatively correlated with carbon emissions, but it is not significant. There is not enough evidence that China may reduce carbon emissions through R&D expenditures, which may be due to "development thirst". China's blind pursuit of economic development has led to institutional arrangements concerning environmental protection giving way to the requirements of economic development, and R&D expenditures have therefore tended to be used for technological research and development to improve capital and labor efficiency, while ignoring the improvement of environmental protection technologies and energy efficiency. The impact of FDI on carbon emissions has been significantly positive. Foreign-funded enterprises have not brought advanced concepts such as low-carbon economy and energy-saving and emission reduction to China, but there has been a so-called "Race to the Bottom" or "Delaware Effect".

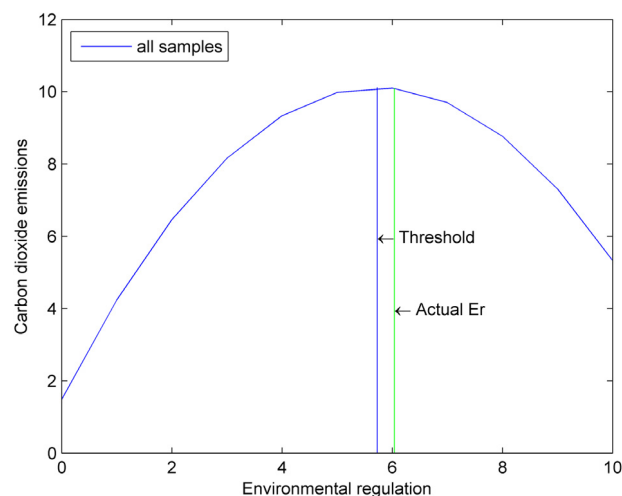
Models 2 and 3 test the impact of environmental regulation on carbon emissions. The results of Model 2 show that the primary coefficient of environmental regulation is significantly positive at the level of 1%, indicating that environmental regulation does not effectively curb carbon emissions, but instead leads to the phenomenon of "green paradox" effect. The results of Model 3 show that the coefficient of environmental regulation is significantly positive, and the square of environmental regulation is significantly negative at the 1% level, indicating that there is inverted U-shaped curve relationship between environmental regulation and carbon emissions. This means that there is a threshold for the effect of environmental regulation on carbon emissions. When the intensity of environmental regulation is less than the threshold, the increase in the intensity of environmental regulation promotes the growth of carbon emissions, resulting in the adverse effect of the "green paradox". When the intensity of environmental regulation exceeds the threshold, the inhibition of environmental regulation on carbon emissions becomes the main role, and thus achieves the expected goal of environmental regulation. According to the regression results of Model 3, the inflection points of the environmental regulation to the U-shaped curve of CO2 emissions and CO2 emissions intensity can be calculated to be 5.73 and 4.92 respectively, that is, the ratio of investment in industrial pollution control

**Table 4**

Full sample empirical results on the relationship between environmental regulation and carbon emissions.

Variable	Dependent variable: Ce			Dependent variable: CeI		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
$C_{t-1}$	1.0190*** (35.21)	0.9207*** (29.87)	1.1245*** (26.40)	0.3481*** (6.05)	0.3784*** (9.32)	0.3170*** (8.78)
$Er$		1.0591*** (4.05)	3.0140*** (5.76)		3.7102*** (3.98)	6.4739*** (6.58)
$Er^2$			-0.2630*** (-5.66)			-0.6572*** (-10.51)
$Y$	1.6020*** (8.17)	1.4835*** (6.93)	1.3441*** (6.59)		1.8690*** (6.43)	3.6124*** (7.12)
$Y^2$	-0.1378*** (-5.54)	-0.1207*** (-4.34)	-0.1178*** (-4.48)		-0.3371*** (-7.24)	-0.8671*** (-2.33)
$Ins$	0.3782*** (4.60)	0.3834*** (4.67)	0.3678*** (4.73)	1.6309*** (11.73)	1.8310*** (9.83)	0.9120*** (15.31)
$Ens$	0.4801*** (14.02)	0.4708*** (13.50)	0.4591*** (13.90)	0.9847*** (4.48)	1.0189*** (3.71)	1.3681*** (2.99)
$Tel$	-0.0100 (-1.31)	-0.0094 (-1.05)	0.0031 (1.25)	-0.4293 (-1.01)	0.1963 (1.44)	0.4981 (1.01)
$FDI$	0.0872*** (4.08)	0.0901*** (4.21)	0.1139*** (5.50)	0.7273*** (5.59)	0.8507*** (6.69)	0.7305*** (9.77)
$Peo$	0.4304*** (3.84)	0.4227*** (3.77)	0.5544*** (5.11)	1.6391*** (3.98)	1.9965*** (4.21)	1.8840*** (1.99)
$_{-}cons$	2.0626*** (4.58)	2.1935*** (4.77)	1.4858*** (6.87)	2.0961*** (5.19)	1.7729*** (7.70)	1.3907*** (10.92)
obs	360	360	360	360	360	360
AR(2)	0.264	0.808	0.323	0.241	0.485	0.638
Hansen	0.775	0.785	0.746	0.709	0.640	0.638

Note: the value in the parenthesis is t-statistic or z-statistic; \*, \*\*, \*\*\* denote 10%, 5% and 1% significance level, respectively. AR (2) and Hansen represent P values of Arellano–Bond test for AR (2) and Hansen test, respectively.

**Fig. 5.** Effect of environmental regulation on CO2 emissions.

to the industrial added value reached 5.73% and 4.92% respectively, the "green paradox" effect will be transitioned to the "back-forced reduction" effect. According to the descriptive statistics in Table 3, the average ratio of investment in industrial pollution control to the industrial added value is 6.04, which exceeds the thresholds of 5.73 and 4.92. This means that China's environmental regulation policies can effectively suppress carbon emissions (see Figs. 5 and 6).



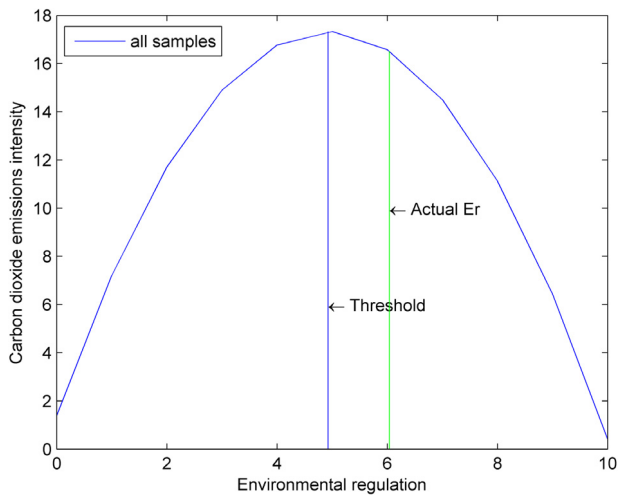


Fig. 6. Effect of environmental regulation on CO2 emissions intensity.

#### 4.2.2. Regression results in different periods

Table 5 reports the empirical results for the three time periods 2004–2007, 2008–2011, and 2012–2015. By comparing the coefficients of the control variables for the three time periods, we can see that China's development model has undergone important changes. The positive contribution of industrial structure, technology level and foreign direct investment on CO2 emissions and CO2 emissions intensity has gradually weakened. In particular, the coefficient of technical level has decreased from 0.0289 in period 1 to  $-0.0077$  in period 3, and the coefficient of technical level in period 3 is significant at the level of 10% significance. That means the role of technological innovation in reducing carbon emissions began to show. Changes in the industrial structure, technology level, and foreign direct investment coefficient also indicate that China's development approach has gradually shifted from extensive to intensive sustainable development. By comparing the coefficient of environmental regulation and the square of environmental regulation, we can see that the impact form of environmental regulation has undergone a significant change. In general, there is a significant inverted U-shaped curve relationship between environmental regulation and carbon emissions. Only when environmental regulation exceeds a certain threshold, the expected goals can be achieved. Figs. 7 and 8 show the relationship between environmental regulation, CO2 emissions, and CO2 emissions intensity in the three periods. By comparison, it can be seen that although the curve types of the three periods are all inverted U-shaped, the curve gradually becomes flat which confirms the role of environmental regulation in energy conservation and emission reduction. The shift of the threshold to the left reflects the good transition of China's development mode, that is, carbon emissions reduction can be achieved through appropriate environmental regulations. By comparing the actual average of environmental regulation expenditures and corresponding thresholds in the three periods, we can see that the role of environmental regulation has gradually been reduced to the "back-forced reduction" effect in period 3 by the "green paradox" effect in period 1. In general, environmental regulation achieves the desired goal of reducing carbon dioxide emissions and carbon emissions intensity.

#### 4.2.3. Regression results in different regions

Table 6 shows the empirical results of the relationship between environmental regulation and carbon emissions in the western region, the central region, and the eastern region. By comparing the coefficients of control variables, it can be seen that there are

Table 5

Empirical results of the relationship between environmental regulation and CO2 emissions in different periods.

Variable	Dependent variable: Ce			Dependent variable: CeI		
	Period 1	Period 2	Period 3	Period 1	Period 2	Period 3
$C_{t-1}$	1.8716*** (9.77)	1.3169*** (7.49)	1.3760*** (16.38)	0.4497*** (10.42)	0.4787*** (5.06)	0.4218*** (11.61)
$Er$	4.0193*** (3.89)	3.7217*** (4.21)	2.8606*** (3.07)	6.3916*** (2.99)	6.6007*** (2.01)	5.5229*** (3.33)
$Er^2$	$-0.3181^{**}$ (-1.99)	$-0.3353^{***}$ (-4.64)	$-0.2883^{**}$ (-2.10)	$-0.6801^{\dagger}$ (-1.73)	$-0.7819^{***}$ (-3.13)	$-0.7023^{***}$ (-4.17)
$Y$	1.1184*** (7.22)	1.5032*** (5.19)	1.0977*** (5.82)	4.1738*** (4.44)	3.8323*** (3.98)	3.6047*** (4.01)
$Y^2$	$-0.2983^{***}$ (-3.31)	$-0.1593^{***}$ (-4.09)	$-0.1027^{**}$ (-1.99)	$-1.0369^{***}$ (-8.30)	$-0.9312^{***}$ (-7.11)	$-0.8004^{***}$ (-5.97)
$Ins$	0.4285*** (3.37)	0.1860* (1.77)	0.1959*** (3.94)	0.9847*** (9.69)	0.9030*** (6.10)	0.8301*** (6.89)
$Ens$	0.5794*** (9.91)	0.4818*** (14.80)	0.4207*** (5.52)	1.4931*** (3.19)	1.3028*** (4.21)	1.1219*** (3.85)
$Tel$	0.0289 (1.20)	0.0091 (1.49)	$-0.0077^{\dagger}$ (-1.74)	0.5012 (0.91)	0.4839 (1.03)	0.3738 (0.87)
$FDI$	0.2094* (1.74)	0.1225*** (3.05)	0.0073*** (3.39)	0.7592*** (4.99)	0.6019* (1.73)	0.482 (1.41)
$Peo$	0.6719*** (4.01)	0.6191*** (5.27)	0.4987*** (3.77)	2.2071*** (3.89)	1.9937*** (6.92)	1.6704*** (3.73)
$-cons$	2.2810*** (5.88)	1.7391*** (4.10)	1.0372*** (7.69)	1.9594*** (7.91)	1.4247*** (5.33)	1.2981*** (8.29)
$obs$	120	120	120	120	120	120
$AR(2)$	0.423	0.217	0.363	0.657	0.264	0.631
$Hansen$	0.567	0.592	0.641	0.612	0.594	0.528

Note: the value in the parenthesis is t-statistic or z-statistic;  $^{\dagger}$ ,  $^{**}$ ,  $^{***}$  denote 10%, 5% and 1% significance level, respectively. AR (2) and Hansen represent P values of Arellano–Bond test for AR (2) and Hansen test, respectively.

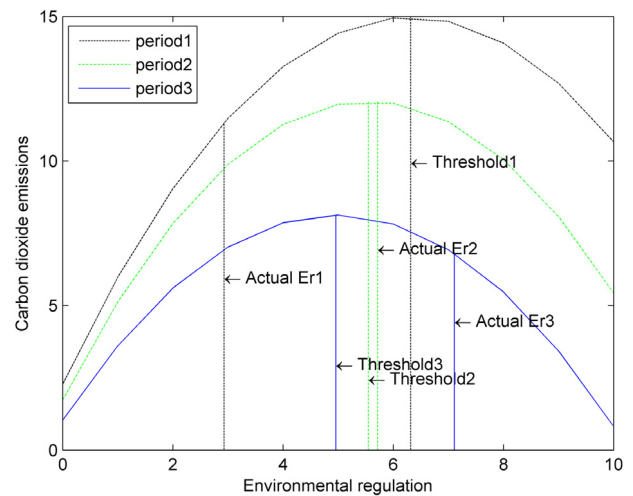


Fig. 7. Relationship between environmental regulation and CO2 emissions in different periods.

huge differences in the development methods, the economic basis of energy conservation and carbon emissions reduction. Benefiting from the rapid economic development, the accumulation of talents and technology, the eastern region has formed good external conditions for energy conservation and emission reduction. Through technological innovation and the introduction of high-quality foreign capital, the eastern region can effectively reduce carbon dioxide emissions. Compared with the central region and the western region, the eastern region has a weaker positive impact on carbon emissions from the industrial structure and energy consumption

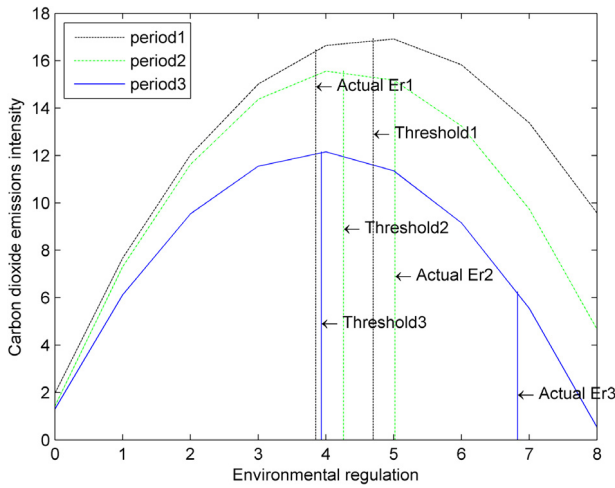


Fig. 8. Relationship between environmental regulation and CO2 emissions intensity in different periods.

structure. This is due to the high technological content of the industrial sector and the improvement in the efficiency of coal utilization. For the central and western regions, the development of the economy may still be the top priority, and the pressure for energy conservation and carbon emissions reduction will be greater. By comparing the coefficient of environmental regulation and the square of environmental regulation, and the relationship between environmental regulation and carbon emissions shown in Figs. 9 and 10, we can see that the inverted U-shaped relationship is still established, but the curve of the eastern region is more flat, that is, the external environment to reduce carbon emissions is better. When the environmental regulation in the central and western regions has not crossed the corresponding threshold, the growth trend of CO2 emissions and CO2 emissions intensity tends to converge, but the threshold in the central region is small due to the better economic base and technological foundation. By comparing the actual average of environmental regulation expenditures and the corresponding thresholds, we can see that the role of environmental regulation in the eastern region and the central region is mainly reflected in the “back-forced reduction” effect, but the western region is represented by the “green paradox” effect. By comparing the functional forms of environmental regulation in the three regions, we can see that appropriate intensity should be set for different geographical characteristics so as to maximize the effectiveness of environmental regulation.

4.3. Robustness test

We use the following measures to test the robustness of the main results. First, we replaced the environmental regulation metrics with the ratio of investment in industrial pollution control to industrial fixed asset investment. After changing the metrics, although the significance level of individual variables changed slightly, the main estimation results are not significantly changed in quality. In addition, we use the systematic GMM method to estimate the model reappearance. After changing the estimation method, the main results did not change significantly except for the slight change in the significance level of individual variables.

4.4. Peak forecast of China’s CO2 emissions and CO2 emissions intensity

Based on the regression results of Model 3, removing the insignificant control variables and taking the coefficients into Eq. (5),

Table 6

Empirical results of the relationship between environmental regulation and CO2 emissions in different regions.

Variable	Dependent variable: Ce			Dependent variable: Ce <sub>i</sub>		
	Western region	Central region	Eastern region	Western region	Central region	Eastern region
C <sub>t-1</sub>	1.6211*** (7.37)	1.2869*** (8.45)	0.9241*** (10.16)	0.2846*** (11.44)	0.4052*** (4.83)	0.7247*** (6.88)
Er	3.8914* (1.79)	4.7108*** (5.61)	2.9473** (2.41)	6.9993*** (11.53)	6.0307** (2.22)	6.1138*** (7.86)
Er <sup>2</sup>	-0.3481*** (-3.36)	-0.5219* (-1.81)	-0.3181*** (-5.81)	-0.4965*** (-4.91)	-0.5917*** (-3.95)	-0.7288*** (-8.20)
Y	2.0166*** (4.99)	1.3719*** (7.27)	1.1026*** (3.90)	4.7299*** (4.11)	2.7814*** (3.86)	3.7421*** (7.52)
Y <sup>2</sup>	-0.2740* (-1.84)	-0.2119* (-1.80)	-0.0914*** (-3.76)	-1.0241*** (-9.60)	-1.3812*** (-3.69)	-0.6910*** (-5.81)
Ins	0.4083*** (3.82)	0.2443* (1.90)	0.1007 (1.21)	0.9963*** (4.91)	0.8257*** (16.32)	0.5320*** (6.28)
Ens	0.5106** (2.61)	0.6793*** (4.78)	0.3742*** (3.99)	1.3891*** (3.75)	1.5926*** (8.00)	1.0828*** (4.65)
Tel	0.0519 (1.04)	-0.0058 (-1.33)	-0.0314** (-2.21)	0.7382 (0.96)	0.6188 (1.33)	-0.2838 (-0.81)
FDI	0.1836** (2.18)	0.1639* (1.89)	-0.0816*** (-3.61)	1.2833*** (8.31)	0.5718* (4.90)	0.6995 (1.06)
Peo	0.5682*** (4.38)	0.4715*** (5.92)	0.6710*** (3.77)	3.7100*** (14.57)	2.4191*** (7.10)	1.5328*** (9.44)
_cons	2.9865*** (7.05)	2.0411* (1.98)	2.1207** (2.12)	2.3546*** (20.91)	1.7793*** (4.49)	1.0273*** (11.62)
obs	108	108	144	108	108	144
AR(2)	0.284	0.421	0.564	0.247	0.342	0.352
Hansen	0.554	0.501	0.624	0.498	0.439	0.601

Note: the value in the parenthesis is t-statistic or z-statistic; \*, \*\*, \*\*\* denote 10%, 5% and 1% significance level, respectively. AR (2) and Hansen represent P values of Arellano–Bond test for AR (2) and Hansen test, respectively.

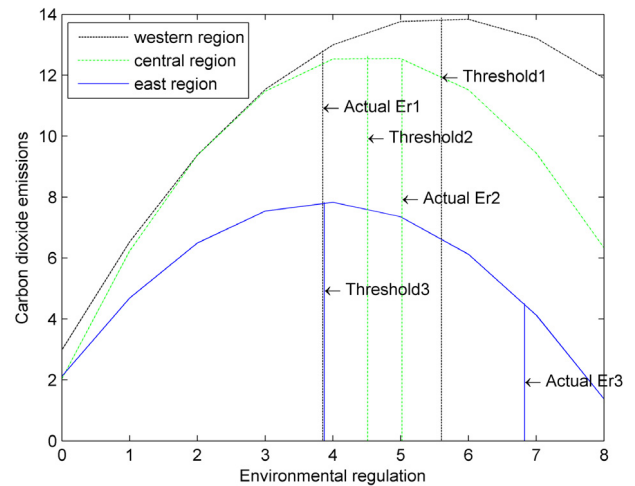
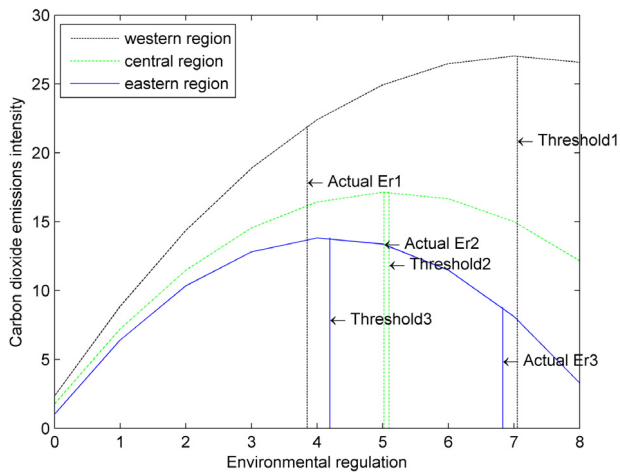


Fig. 9. Relationship between environmental regulation and CO2 emissions in different regions.

we can get the equations for the relationship between environmental regulation and CO2 emissions and CO2 emissions intensity:

$$\begin{aligned}
 \ln Ce_{i,t} = & (1.1245) \ln Ce_{i,t-1} + (3.0140) \ln Er_{i,t} \\
 & + (-0.2630) (\ln Er_{i,t})^2 + (1.3441) \ln Y_{i,t} \\
 & + (-0.1178) (\ln Y_{i,t})^2 + (0.3678) \ln Ins_{i,t} \\
 & + (0.4591) \ln Ens_{i,t} + (0.1139) \ln FDI_{i,t} + (0.5544) \ln Peo_{i,t} \\
 & + 1.4858
 \end{aligned} \tag{7}$$



**Fig. 10.** Relationship between environmental regulation and CO2 emissions intensity in different regions.

$$\begin{aligned} \ln Ce_{i,t} = & (0.3170) \ln Ce_{i,t-1} + (6.4739) \ln Er_{i,t} \\ & + (-0.6572) (\ln Er_{i,t})^2 + (3.6124) \ln Y_{i,t} \\ & + (-0.8671) (\ln Y_{i,t})^2 + (0.9120) \ln S_{i,t} \\ & + (1.3681) \ln S_{i,t} + (0.7305) \ln FDI_{i,t} + (1.8840) \ln Peo_{i,t} \\ & + 1.3907 \end{aligned} \quad (8)$$

According to the formula of the vertex for the quadratic curve, it can be predicted that the peak value of CO2 emissions is 643863.2853 million tons, and the peak value of per capita real GDP (based on 2004 as the base period) is 48195.60 yuan. The peak of CO2 emissions intensity is 364,232 tons/yuan, and the peak per capita real GDP is 6139.93 yuan. At the same time, by bringing China's average per capita real GDP of RMB22,251.0 from 2004 to 2015 into Eq. (8), the peak value of China's CO2 emissions intensity at the current stage is 218.864 million tons/yuan, which is only half of the predicted value. It shows that China's environmental regulation policies are effective in energy conservation and emissions reduction, and investment in environmental regulation has made the EKC curve of carbon emissions intensity flattened and the peak value decreased. According to the results of the panel data, the per capita real GDP growth rate is above 9.5%. In 2012, the average real GDP per capita of 30 provinces has reached 27,589.68 yuan. Although China's economic growth rate has decreased since 2015, and the conservative estimate of China's annual per capita real GDP growth rate is 5% in the next few years, the per capita real GDP will reach 49,861.39 yuan by 2030, reaching the predicted peak GDP of 48,195.60 yuan in advance. If the Chinese government continues to maintain current environmental regulation policies and increase investment in environmental protection, it can be expected that the EKC curve of CO2 emissions will become flat and the actual peak value of carbon emissions will decrease.

## 5. Conclusions and policy recommendations

Based on the panel data of 30 provinces in China during 2004–2015, this research analyzes the impact of China's environmental regulation on carbon emissions by using the Tapio decoupling model, the differential GMM method, and the peak forecasting method. We can get the following conclusions:

To start with, by analyzing various indicators of decoupling, we can see that the dependence of China's 30 provinces on fossil energy experienced a process from weak to strong and then weak, and the economic growth mode experienced a process from intensive to extensive and then intensive relative.

Next, there is a Kuznets curve for carbon emissions. Optimizing the energy consumption structure and industrial structure has a positive impact on reducing CO2 emissions and CO2 emissions intensity. Specifically, if the ratio of coal consumption to total energy consumption decreases by 1%, the carbon emissions and carbon intensity will decrease by 0.4591% and 1.5409%, respectively. When the ratio of the secondary industry's output value to GDP is reduced by 1%, the carbon emissions and carbon intensity will be reduced by 0.3678% and 0.9120%, respectively. Although China's assessment standards for FDI have been increasing year by year, such as encouraging the introduction of high-quality foreign capital and controlling the entry of high-pollution, high-energy-consuming foreign capital, it has not escaped the dilemma of the "pollution paradise". The increase in R&D expenditures did not significantly reduce carbon emissions. The reason may be that China's current R&D expenditures are more inclined on improving capital and labor efficiency, while ignoring technological investment for improving environmental protection and energy efficiency.

Finally, there is a significant inverted U-shaped curve relationship between environmental regulation and CO2 emissions and CO2 emissions intensity. Only when the environmental protection investment reaches a certain threshold can environmental regulations actually achieve the goal of reducing emissions. China's environmental regulation policies can generally restrain carbon emissions, and the average environmental protection investment exceeds the threshold of 5.73%. Regression results for different periods showed that the inverted U-shaped curve of environmental regulation policies and carbon emissions gradually became flat and the threshold gradually shifted to the left, which also confirmed the role of environmental regulation in energy conservation and emissions reduction. Especially in period 3, the "green paradox" effect has been replaced by the "back-forced reduction" effect. Regression results for different regions show that the effect of environmental regulation in the eastern region is better than that in the central region and the western region. In particular, the intensity of environmental regulation in the western region should be further optimized. The results of CO2 emissions and CO2 emissions intensity peak predictions also indicate that the long-term investment in environmental protection has made the EKC curve of CO2 emissions and CO2 emissions intensity smoother, corroborating the effectiveness of environmental regulation policies.

The policy recommendations in this article are as follows:

Firstly, strengthen the intensity of environmental regulations appropriately. At the current stage, the environmental regulation has exerted the expected "back-forced reduction" effect. Therefore, appropriate strengthening of environmental regulations will help reduce carbon emissions. However, we must also be vigilant to follow the trend of unrealistic blindly improving the intensity of environmental regulation so that the impact of environmental regulation on the carbon emissions trajectory appears to be reversed to N-type, again triggering the "green paradox" effect. Second, the government should set the environmental regulation intensity based on the heterogeneity of regional economic development levels and carbon intensity. For the eastern developed provinces, taking into account the increasing demands for environmental quality and the demand for green products, it is advisable to adopt a higher level of environmental regulation intensity. For the underdeveloped provinces of the central and western regions, we cannot blindly pursue economic growth while neglecting the quality of the environment, and the intensity of the environmental regulation set should be moderate.

Secondly, optimize energy consumption structure. The coal-based energy consumption structure will obstruct China's long-term goal of carbon reduction, and achieving the low-carbon energy consumption structure must be based on the development of clean energy and improving energy efficiency. On the one hand, the

government should actively encourage the development of a safe and clean energy supply and consumption system, and promote the application and popularization of green energy such as wind power and solar energy. On the other hand, the government should improve the efficiency of energy use, especially the utilization of coal resources, and achieve various goals such as energy saving, consumption reduction, pollution control, and carbon reduction.

Thirdly, play a positive effect of technological innovation on reducing carbon emissions. The empirical results show that under the constraints of environmental regulation, technological innovation has not significantly reduced carbon emissions. Therefore, the government should adopt targeted incentive policies according to local conditions, create an external environment conducive to corporate environmental protection technology innovation, and guide the transfer of innovation inputs to environmental protection technologies. Enterprises should actively introduce environmental protection technologies that match their own productivity levels and technological absorptive capacity, conduct reverse learning and secondary development, give full play to the advantage of late development, and realize the dynamic evolution from technology import to technology imitation to independent innovation.

Fourthly, optimize the strategy of attracting and using foreign capital to increase its environmental spillover effect. On the one hand, although high-intensity environmental regulation may hinder the inflow of foreign-funded enterprises, if local governments loose their environmental regulations, they may attract inflows of high-energy-consuming and highly-polluting enterprises, and scare off low-energy and low-pollution types. Therefore, local governments cannot simply ignore the quality of foreign investment in order to attract foreign investment, eliminate the introduction of high-pollution foreign-funded enterprises, and avoid becoming a “pollution paradise” for developed countries. On the other hand, to strengthen the central government’s guiding role in the process of attracting foreign investment, formulate appropriate investment targets according to the factor endowment conditions of different regions, coordinate and coordinate policies for attracting investment in different regions, and prevent inter-regional competition in attracting foreign capital so as to avoid reducing the environment regulatory level, and increase the environmental spillover effect of foreign capital.

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