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Reconsidering the relationship between CO₂ emissions and economic growth: New evidence from China during 1990–2016

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ABSTRACT

Coal use has caused the degradation of air quality. Since 2006, leading economies such as China and the United States have emitted more CO_2 than other countries have. According to the statistics of the International Energy Agency, China ranks first in CO_2 emissions in the world. Moreover, according to the data of the United Nations, China is the most populous country in the world. Therefore, attention should be paid to China's carbon emission problem. According to the environmental Kuznets hypothesis, the anthropogenic pressure on the environment is not expected to increase indefinitely as economy grows but to decrease when gross domestic product (GDP) exceeds a certain level. Researchers should examine whether China's CO_2 emissions have peaked and whether China's GDP growth is the main cause of the increase in its CO_2 emissions. The aforementioned topics are related to the global environmental economy and energy efficiency and thus deserve attention. To examine the relationship between environmental quality and economic growth, the variations in the aforementioned parameters in China over time were examined. In structural estimation, the environmental Kuznets hypothesis and regression discontinuity test were used to empirically demonstrate that the environmental Kuznets curve has an upward slope; thus, although pollution increases with income, the slope of the pollution versus income graph is less than 1 and becomes more concave over time. This phenomenon can be largely attributed to the 1997 Asian financial crisis, which played an important role in the formation of an inverse U-shaped relation between China's economic growth and CO_2 emissions.

INTRODUCTION

CO_2 emissions from fuel combustion are affected by various factors, including population growth, gross domestic product (GDP), and energy supply. Carbon emissions exacerbate global climate change. Transitioning away from coal energy is a cost-effective method for achieving a low-carbon economy. Over the past decade, coal power has been replaced by natural-gas-fired, wind, and solar power in some countries. As the world's largest CO_2 producer, China faces the challenge of reducing the carbon intensity of its economy while also achieving economic growth. Researchers should examine whether the stages of economic development or modes of production directly affect China's carbon dioxide emissions. China's environmental protection tax, which was implemented in 2018, has formally replaced the "pollution discharge fee" that was enforced since 1982. For the first time, privately owned businesses have been included as targets of the environmental tax. However, emissions from vehicles and vessels are exempted under the aforementioned tax. In addition, carbon dioxide emissions are also exempted from tax. According to the statistics of the International Energy Agency (IEA) and

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China's Statistical Yearbook, China's CO_2 emissions were approximately 1.76 billion tons in 1984. From 1984 to 1996, CO_2 emissions in China exhibited an upward trend. CO_2 emissions were 2.926 billion tons in 1997 and 3.021 billion tons in 1998. Surprisingly, CO_2 emissions decreased to 2.92 billion tons in 1999. Since then, with the recovery of China's economy and the growth of energy demand, CO_2 emissions have reached a record high of 9.19 billion tons in 2013. However, after 2014, CO_2 emissions began to decrease gradually each year.

The remainder of this paper is organized as follows. First, a brief review of the related literature is provided. Then, we describe the research model and the method for verifying the environmental Kuznets hypothesis. Moreover, we provide evidence for the interaction among CO_2 emissions, total primary energy supply (TPES), vehicle purchase tax, pollution fee levy, and coal supply in China and detect China's environmental Kuznets inflection point. China's coal consumption did not increase but dramatically decreased during the 1997 Asian financial turmoil. China also experienced high economic growth during the aforementioned period. We provide possible explanations for our findings by performing regression discontinuity (RD) checks for key parameters of the developed model. The conclusions of this study are presented in the Conclusion section.

LITERATURE REVIEW

This study is related to several strands of theoretical and experimental research. One of these research strands is relationship between income policies and environmental improvement. Panayotou (1997) collected data for 1982–1994 from 30 countries and revealed that low-income policies have a positive effect on improving the environment. The aforementioned effect increases with an increase in the income level. Thus, the faster the economic growth, the higher is the population density and the environmental cost of economic growth (Zoundi, 2017). Grossman and Krueger (1995) regarded urban air pollution and oxygen content in river water as environmental indicators. Through regression analysis, Grossman found that economic growth causes the deterioration of environmental indicators in the low-income stage, but these indicators improved at a certain stage of development. The inflection point occurs at a per capita income level of $8,000 (Grossman and Krueger, 1991, 1995; Sherry and Kelly, 2008; Stern, 2004; Gürlük, 2009). Kebede et al. (2010) examined the causal relationships among economic growth, pollutant emissions, and energy consumption in Sub-Sahara Africa. They suggested that Sub-Sahara Africa must sacrifice economic growth or reduce energy consumption to achieve decreased carbon emissions. However, Richmond and Kaufmann (2006) argued that no significant relationship exists between pollutant emissions and economic development.

Numerous studies have argued that a relationship exists between environmental quality and economic development. For example, Bruyu (1997) examined data for the 1980s from developed countries and determined that transformation in the economic structure has no significant effect on SO_2 emissions; however, in the high-income stage, the environmental policies created due to international agreements may explain the negative correlation between the environment and income. Harbaugh et al. (2002) indicated that the link between economic growth and environmental pollution is not only influenced by economic factors but also by sample selection and research methods (Stern and Common, 2001). Many studies have examined the application of the environmental Kuznets curve (EKC), which indicates the aggregate relationships between pollutants and a country’s income for various environmental health indicators, such as air pollution. The Kuznets curve exhibits an inverse U shape with an increase in the per capita income and GDP. Llorca and Meunie (2009) obtained an N-curve relationship between SO_2 emissions and the per capita income. Friedl and Getzner (2003) focused on data from Austria for 1960–1999 rather than on panel or cross-section data for a set of countries to test whether an EKC relationship exists for a certain country. They obtained that an N-shaped EKC result for Austria. Many studies have supported the EKC hypothesis. For example, Cole (2003) indicated that a reasonably robust inverse U-shaped relationship exists between per capita income and emissions. Brian et al. (2004) analyzed the relationships among economic growth, international trade, and environmental pollution and obtained inverse U-shaped curves for these relationships. Copeland noted that economic growth, international trade, and capital flow considerably influence environmental pollution. Halkos and Tzeremes (2013) proposed a conditional directional distance function to estimate the link between regional environmental efficiency and per capita income. They obtained an inverse U-shaped relationship between the aforementioned factors. Levinson and O'Brien (2019) stated that the environmental Engels curve (EEC) indicates the relationship between household income and the pollution associated with the goods and services consumed. However, the EEC approach cannot be used to analyze the EKC problem of why middle-income countries historically have a higher pollution level than poor and rich countries. Suri and Chapman (1998) suggested that the EKC mechanism may be facilitated by advanced economies exporting their pollution-intensive production processes to less-developed countries. It is unclear why economic growth leads to improved environmental quality. One reason for this phenomenon could be that people's demands regarding their living environment increase with an increase in their income. Andrzej and Kuchta (2020) proposed an indicator of GDP based on satellite nighttime light data to examine the empirical evidence documenting an inverse U-shaped relationship between income and CO_2 emissions from fossil fuels. Empora et al. (2020) suggested that abatement is one of the driving forces for the emergence of EKC. Existing studies on EKC theory have mainly examined the influence of abatement technologies on the utility function and have addressed the elasticity of substitution in preferences between income and environmental quality that decreases when the relative scarcity of the environment increases (Figueroa and Pastén, 2013; 2015). Stern (2006) stated that if the world invests 1% of the global GDP per year to combat global warming, it would avoid 5%–20% of GDP loss per year in the future. The concentration of particulate matter (PM) 2.5 ($PM_{2.5}$) is regularly measured from fixed-site, population-oriented monitors located within metropolitan areas. Although PM is measured by thousands of locations throughout the world, the number of monitor stations in different geographical areas varies with some areas having little or no monitoring. Therefore, the annual urban mean concentration of $PM_{2.5}$ is estimated through improved modeling by integrating data from satellite remote sensing, population estimates, topography measurements, and ground measurements. The estimates of $PM_{2.5}$ for data-poor countries may be relatively imprecise when $PM_{2.5}$ measurements are unavailable. This imprecision can result in apparently abrupt changes in air pollution levels at borders with data-poor countries. Therefore, to enhance the accuracy of the data source, countries must continue to improve their ground measurements. To evaluate the relationship between CO_2 emissions and economic growth in line with most current studies, this study used CO_2 emissions, which is the main gas responsible for global warming, as an indicator of air pollution in a country (Mikayilov et al., 2018). Akbostanci et al. (2009) claimed that the extent of environmental degradation can be assessed by analyzing the development path of a single country only. China is the most populous country in the world, and its economy has been growing rapidly in recent decades. Therefore, in this research, we considered China as a case study and established a robust theoretical model. We then used official data to detect whether an EKC inflection point or unknown bounded disturbances exist.

METHODOLOGY AND EMPIRICAL ANALYSES

The conventional reduced-form EKC regression is associated with some time-series problems because EKC is a long-term phenomenon in an economy. In this study, we carefully examined the time-series properties of the selected dependent and explanatory variables before performing any regression. First, we developed a simple and straightforward static model of the microfoundations of this relationship. Unlike other studies, we used EKC theory combined with the RD approach to determine the relationship between environmental degradation costs and economic growth in China. From a methodological viewpoint, inferences drawn from a well-implemented RD test have comparable internal validity to conclusions obtained through analysis by using nonlinear multivariate models. To the best of the authors' knowledge, this study is the first to combine an EKC theoretical model with the RD approach.

EKC enforcement

We present a theoretical model of the inflection point of the EKC in the following text. Equation 1 describes the indirect utility between environmental pollution and economic growth. We assume that the utility function is separable into two arguments, namely *R* and *W*, with the additive separable function and additive preferences. In the developed model, the pollution emissions generated in the production process are included in the production function to meet the extractive service of the natural environment to the production behavior of the economic system (Bovenberg and Smelters, 1995) such that the following equation is satisfied:

$$\mathrm{V} = s_1 - s_2 \times e^{-\frac{R}{\delta}} - \gamma \times \mathrm{W} \tag{1}$$

Where R represents the real income; W, denotes the pollution emissions; s_1 and, s_2, γ, and $\delta > 0$, where $s_1$is a coefficient, $s_2$reflects the effect of the real income on utility, and γ reflects the effect of the generated emissions on utility.

We assume that the marginal disutility of pollution emissions remains unchanged. To eliminate structural effects, we used only one commodity model for analysis. According to the study data, a large number of firms produce an aggregate output Y by using a constant returns-to-scale technology of the Cobb–Douglas type. Therefore, the income of a country (Y) is expressed as follows:

$$\mathrm{Y} = \mathrm{P} \times \lambda \times \mathrm{W}^{\alpha} \times \mathrm{F}(\mathrm{K}, \mathrm{AL})^{1-\alpha} \tag{2}$$

Where λ is the conversion coefficient; *P* represents the commodity price, with $\lambda \in (0,1)$; F(K,AL) is an aggregate production function, where K denotes the aggregate physical capital and *L* represents the aggregate labor employed in production; and *A* represents the technical level, with $\mathrm{A} > 0$, $\alpha \in (0,1)$. Equation 3 indicates that the marginal output value of pollution emission is equal to the demand of reverse pollution emission.

$$\Gamma^{\mathrm{D}} = \alpha \times \mathrm{P} \times \lambda \times \mathrm{W}^{\alpha-1} \times \mathrm{F}(\mathrm{K}, \mathrm{AL})^{1-\alpha} = \frac{\alpha}{\mathrm{W}} \times \mathrm{Y} \qquad (3)$$

Moreover, the supply utility function of pollutant emissions can be obtained as follows:

$$\Gamma^{\mathrm{S}} = -\frac{\mathrm{V_W}}{\mathrm{V}_Y} = \frac{\gamma \times \Omega(\mathrm{P}) \times \delta}{s_2} \times e^{\frac{R}{\delta}} \qquad (4)$$

The expression of the EKC can be obtained by using Equations 5 and 6 as well as the supply–demand function.

$$\mathrm{W}^* = \frac{\alpha \times s_2 \times R}{\gamma \times \delta} \times e^{\frac{-R}{\delta}} \qquad (5)$$

Furthermore, the following formula can be obtained by calculating the derivative of environmental pollution (*W*):

$$\frac{\mathrm{dW}}{\mathrm{dR}} = \frac{\alpha \times s_2}{\gamma \times \delta} \times \left(e^{-\frac{R}{\delta}} - \frac{1}{\delta} \times R \times e^{-\frac{R}{\delta}}\right) = \frac{(\delta - R)}{R \times \delta} \times \mathrm{W} \qquad (6)$$

The inflection point of environmental pollution occurs when $R = \delta$. When economic growth reaches the level of δ, environmental pollution can be alleviated. Thus, people begin to pay attention to the issue of sustainable environmental management. Equation 6 expresses a convergence function whose value is greater than 0. If n positive convergence functions are added together, the function obtained should also be convergent.

By using the theoretical models derived from Equations 1–6, we performed empirical analyses to determine whether the EKC existed in China's air pollution emissions and GDP data over the past 27 years. The nonexistence of the EKC indicates that with an increase in economic growth, environmental pollution emissions would increase and the ecological environment would continue to be destroyed.

Path and time required to reach the EKC inflection point

According to Equations 1–6, the time required to reach the inflection point of the EKC when the real income or GDP of a country is known can be derived as follows:

$$\delta = R \times (1+g)^N \qquad (7)$$

Where *R* represents the real income; *g* is the average annual growth rate of China's GDP from 1990 to 2016; and *N* is the number of years, that is, the time required by a country to reach the EKC inflection point, which can be calculated using Equation 8.

$$\mathrm{N}^* = \frac{\ln \frac{\delta}{\mathrm{R}}}{\ln(1+g)} \qquad (8)$$

Data

According to the IEA, most of China's energy demand is met by coal energy. Moreover, most of the coal consumed in China is mined in China itself. We use China as an example to illustrate the calculation of the total energy supply (in ktoe). The proportion of coal in the total energy supply is expressed in brackets. The total energy consumption in China in 1990, 1995, 2000, 2005, 2010, 2015, and 2016 was 530, 516 Ktoe (61%), 648, 032 Ktoe (62%), 664, 720 Ktoe (59%), 1, 203, 693 Ktoe (68%), 1, 790, 421 Ktoe (71%), 1, 996, 620 Ktoe (67%), and 1, 916, 209 Ktoe (65%), respectively. Reducing the proportion of coal supply in the total energy supply is the core of reducing carbon emissions. According to the aforementioned observations, this study includes two critical variables, namely vehicle purchase tax and pollution fee levy. Pollution emissions are measured in Mt CO_2; the vehicle purchase tax is measured in 10,000 Yuan; and the carbon emission fee levy is measured in 100 million Yuan. As per China's Vehicle Purchase Tax Law, since July 1, 2019, the taxable price when taxpayers purchase vehicles for their personal use depends on the total price paid by them to sellers, excluding VAT; the vehicle purchase tax; and the pollution fee levy data of the National Bureau of Statistics of China and China Statistical Yearbook of 2018. Moreover, data regarding CO_2 emissions, population, GDP, TPES, and coal supply was obtained from the IEA. The vehicle purchase tax is a consumption tax; however, the polluter who directly discharges air pollution is charged a pollution fee, which is in line with the principle of polluter paying.

According to the theoretical models derived from Equation 6, we fit this EKC model to China's income data and structurally analyzed the relationship between environmental degradation costs and economic growth in China. Moreover, we determined if the EKC inflection point existed. We also established a pollution emission loss model based on the EKC hypothesis and introduced relevant variables into the model. In Table 1, *lnloss* indicates the logarithm of the environmental degradation cost caused by air pollution, which is mainly related to carbon dioxide emissions. The parameter *lnCO₂* represents the logarithm of carbon dioxide emissions measured in Mt. Moreover, *lnloss* and *lnCO₂* are dependent variables. The parameter *lnGDP* represents the logarithm of the gross national product in 2010 in billion

Table 1. Environmental Degradation Cost: SUR-OLS (1990–2016).

Independent variable	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**	**Model 8 (I)**
lnGDP	-0.633768 (-1.163962)	**5.576340*** **(4.957335)**	**0.193446** **(1.460805)**	**1.897956*** **(12.92399)**	-0.199397 (-0.359905)	-3.797532* (-4.032505)	**8.180981*** **(8.249898)**	-5.255635* (-5.548564)
(lnGDP)^2	0.082856** (2.432931)	**-0.224783*** **(3.920254)**	**-0.001710** **(-0.192161)**	**-0.044522*** **(-5.321973)**	0.048377 (1.337284)	0.245242* (4.615193)	**-0.451602*** **(-7.929695)**	0.262291* (5.192822)
lnPOPULATION		**-17.28379*** **(-5.816013)**						4.578423*** (2.184505)
lnCOALSUPPLY			**0.774558*** **(20.58857)**					1.407807* (9.484629)
ln(TPES//GDP)				**1.249412*** **(24.80402)**				-0.550272*** (-2.835023)
TPES/POPULATION					0.230068*** (2.044252)			0.012321 (1.193907)
lnEMISSIONFEELEVY						0.530869 (5.508365)		0.077042** (3.443810)
lnVEHICLEPURCHASETAX							**0.144742***** **(1.934957)**	-0.008775 (-0.367507)
AR(1)	1.309846* (6.513925)	0.997779* .(5.097859)	-0.191329** (-0.554599)		1.306810* (6.252795)	1.262288* (4.232701)	1.064240* (3.697230)	-1.656154** (-5.165148)
AR(2)	-0.493201* (-2.255023)			-0.594127** (-2.626970)	-0.496795*** (-1.940219)	-0.582980*** (-1.766222)	-0.752304* (-4.548959)	-0.900716*** (-4.187646)
D) Wstat	0.283584		1.795465	2.298624	0.470959	0.890492	0.883543	3.351773
Adjusted-R^2	0.973502	0.988809	0.998741	0.999004	0.976325	0.988069	0.990605	0.999848
γ*=(lnGDP)* (inflection point of KC)		12.403829	56.56315	20.985802	2.0608657	7.742417	9.057733	

This table presents the variables in the logarithmic form. The symbols *, **, and *** represent significance levels of 1, 5 and 10%, respectively. The numbers in brackets are the *t*-statistics of the estimated parameters. The logarithm of the GDP in 2016 was 9.159573. The data regarding CO_2 emissions, population, GDP, TPES, and *COALSUPPLY* were obtained from the IEA. The vehicle purchase tax and pollution fee levy data were obtained from the National Bureau of Statistics of China.

USD; *(lnGDP)*^{2}, which is a quadratic form, denotes the location and curvature of the EKC; *lnCOALSUPPLY* denotes the logarithm of the energy supply from coal in Mtoe; *ln(TPES/GDP)* represents all major energy supplies as a percentage of GDP; TPES/POPULATION denotes all major energy supplies as a percentage of the population; *lnEMISSIONFEELEVY* is the logarithm of the penalty for pollution discharge; and *lnVEHICLEPURCHASETAX* is the logarithm of the purchase tax of vehicles. We added the variable *lnCOALSUPPLY* to model 1 in Table 1 to obtain model 2 in Table 1. We added different variables to model 1 to obtain other models. The analyses and calculations performed to determine the relationship between environmental degradation costs and economic variables are described in the follow subtopic.

Structural estimation

The summary of the statistics collected from the IEA and China National Bureau of Statistics is presented in Table 1. First, the unit root test indicates whether we can use the sample data in Table 1 to establish SUR-OLS (Seemingly unrelated regressions- ordinary least squares). On the basis of the unit root test and cointegration verification, Wang et al. (2019) used the ADRL bounds test for performing Pesaran cointegration verification (Pesaran et al., 2001; Keho, 2010). Using the integration approach among those variables for China for 1990–2016, the result denotes that $lnCO_2$ affects *lnGDP* but not vice versa. Because *lnGDP* is a dependent variable, it represents one-way cointegration with $lnCO_2$, which is an independent variable. Moreover, when $lnCO_2$ and *lnCOALSUPPLY* are substantially dependent variables, a cointegration relationship exists between them. The results indicate that *lnGDP* and $lnCO_2$ have a one-way long-term positive relationship. An increase in $lnCO_2$ leads to an increase in *lnGDP*; however, an increase in *lnGDP* does not necessarily lead to an increase in $lnCO_2$ (Mikayilov et al., 2018).

Cost analysis of environmental degradation

Equation 9 expresses the time-varying income elasticity of CO_2 emissions as follows:

$$\eta_t = \frac{\partial \ln \mathrm{CO2}}{\partial \mathrm{lnGDP}} = \beta_0 + \beta_1(\frac{\mathrm{t}}{\mathrm{T}}) + \beta_2(\frac{\mathrm{t}}{\mathrm{T}})^2 + \beta_3\cos(\frac{2\pi \mathrm{t}}{\mathrm{T}}) + \beta_4\sin(\frac{2\pi \mathrm{t}}{\mathrm{T}}) + \beta_3\cos(\frac{4\pi \mathrm{t}}{\mathrm{T}}) + \beta_4\sin(\frac{4\pi \mathrm{t}}{\mathrm{T}}) \quad (9)$$

Thus, to display the Kuznets concept, in principle this occurs when

(i) Relative decoupling of $lnCO_2$ and *lnGDP*, whereas $\frac{\partial \ln \mathrm{CO2}}{\partial \mathrm{lnGDP}} < 1, \frac{\partial \mathrm{CO2}}{\partial \mathrm{GDP}} > 0$

(ii) Absolute decoupling of *lnCO2* and *lnGDP*, whereas $\frac{\partial \ln \mathrm{CO2}}{\partial \mathrm{lnGDP}} < 0, \frac{\partial \mathrm{CO2}}{\partial \mathrm{GDP}} < 0$

We used the SUR-OLS method to determine if the EKC existed within China's CO_2 emissions and GDP data over the past 27 years. The absence of the EKC implies that economic growth would cause an increase in pollution, and the environment would continue to be destroyed.

Case 1: Model 1 in Table 1 indicates that a U-shaped relationship exists between the cost of environmental degradation and GDP for China. Only the influences of *lnGDP* and $(lnGDP)^2$ on $lnCO_2$ were considered, and the influence of other parameters was ignored. The Kuznets inflection point did not exist between China's GDP growth and CO_2 emissions during the study period.

- **Case 2:** When the *lnPOPULATION* variable was added into model 1 in Table 1 to obtain model 2 in Table 1, the corresponding regression coefficient was negative and passed the 1% significance test. The aforementioned result indicated that the population had a negative correlation with the cost of environmental degradation. From the regression results, we predicted that an increase in the population is not the main factor for the increase in the cost of environmental degradation in China. If a country continues to develop low-carbon energy resources, such as wind power, solar energy, and hydropower, its carbon emissions may decrease even as the population increases significantly.
- **Case 3:** Model 3 in Table 1 exhibited a regression coefficient of 0.774558 for *lnCOALSUPPLY*, with the significance level being 1%. The positive sign of the coefficient revealed that an increase in coal supply enhanced the cost of environmental degradation to a certain extent.
- **Case 4:** We obtained model 6 in Table 1 by incorporating the *lnEMISSIONFEELEVY* variable into model 1 in Table 1. The corresponding regression coefficient was 0.530869, which did not pass the 10% significance test. China's penalties for environmental pollution in recent years did not reduce environmental degradation costs, which may be one of the reasons why China has replaced penalties with environmental protection taxes since 2018.
- **Case 5:** We obtained model 7 in Table 1 by incorporating the *lnVEHICLEPURCHASETAX* variable into model 1 in Table 1. The corresponding regression coefficient was 0.144742, which passed the 10% significance test. The taxation on vehicle purchases in China is mainly imposed on the users of taxable vehicles. Users with higher consumption ability bear higher taxes than those with lower consumption ability. However, model 7 in Table 1 indicates that taxation on vehicle purchase has no significant influence on reducing the cost of environmental degradation. The vehicle purchase tax in China began to be levied in 2002. In model 5 in Table 1, the *TPES/POPULATION* variable did not pass the 5% significance test. Moreover, in model 6 in Table 1, the effect of *lnEMISSIONFEELEVY* on $lnCO_2EMISSIONS$ did not pass the 5% significance test. In model 7 in Table 1, the effect of *lnVEHICLEPURCHASETAX* on $lnCO_2EMISSIONS$ did not pass the 5% significance test; thus, the estimated coefficient is invalid. Therefore, we did not insert the variables *TPES/POPULATION*, *lnEMISSIONFEELEVY*, and *lnVEHICLEPURCHASETAX* into Equation 9 in the following structural stability estimation.

Mutation point problem

To examine whether major events occurring at

Table 2. Test of specified breakpoints for determining the structural change (1990–2016).

Break point date	Event	Chow test *F*-statistic	Chow forecast likehood-ratio	Ramesy reset *F*-statistic	Omitted other variables	Does event have structural changes to the model during the period?
1997	Asian financial turmoil (I)	6.371545* (0.0017)	252.1371* (0.0000)	0.225678 (0.6399)	No	Yes
1998	Asian financial turmoil (II)	5.535386* (0.0034)	81.11115* (0.0000)	0.225678 (0.6399)	No	Yes
1999	Asian financial turmoil (III)	4.219161* (0.0110)	43.09384* (0.0008)	0.225678 (0.6399)	No	Yes
2008	Global financial Turmoil in America (I)	1.748122 (0.1779)	14.67989 (0.1001)	0.225678 (0.6399)	No	No
2009	Global financial Turmoil in America(II)	1.747541 (0.1780)	1.431133 (0.0263)	0.225678 (0.6399)	No	No

This table presents variables in the logarithmic form. The symbols *, **, and *** represent significance levels of 1, 5 and 10%, respectively. The numbers in brackets are the *p* values of the *F*-statistic. In the Chow test, $F^{\circ} = \frac{S_u-(S_1+S_2)/k}{(S_1+S_2)/(N_1+N_2-2k)}$ follows the F distribution with k and $N_1 + N_2 - 2k$ degrees of freedom, where k is the total number of parameters and N_1 and N_2 represent the number of years before and after the detection time point, respectively. The parameter S_u represents the sum of residual squares of the combined data, S_1 is the sum of residual squares of the first group of data, S_2 is the sum of residual squares of the second group of data, and *lnCO₂* is a dependent variable. The other variables in the table are independent variables.

different time points during the study period (1990–2016) caused structural changes and different estimation coefficients in the research models, we first used the subjective breakpoint algorithm to identify the stability of the parameters in Table 2. We then used the multiple-breakpoint algorithm to estimate the location of breakpoint.

Subjective analysis

Mutation point detection was conducted under a given time-series mutation point. In general, a nonlinear regression model can be estimated using the least square method. In addition, various nonlinear function forms can be obtained through the Box–Cox transformation of the nonlinear function (Box and Jenkins, 1976; Box and Pierce, 1970). We established Equation 10 to explore whether the Asian financial crisis and the global financial crisis (GFC) of 2008–2009 led to a structural transformation of the developed models in Table 1 over the past two decades.

Case 1: The Asian financial crisis from 1997 to 1999

Case 2: The GFC from 2008 to 2009 in the United States

$$lnCO_2EMISSIONt = -2.734206 + 0.205313 lnCOALSUPPLYt - 0.103239 lnPOPULATIONt + 1.490646 lnGDPt + 0.921886 lnTPESGDPt - 0.035384\,(lnGDPt) \quad (10)$$

We conducted Chow verification (Chow, 1960; Dougherty, 2012; Greene, 2012) to detect whether the aforementioned two time periods caused structural transformation of the models in Table 1. The obtained results (Table 2) are described in the following text:

(i) We used the Chow test to identify a structural break in the models (Chow, 1960; Doran, 1989; Wooldridge, 2009). The *p* value of *F*-statistics in Table 2 indicates that the Asian financial crisis from 1997 to 1999 caused structural changes in the nonlinear relationship between the *lnGDP* and *lnCO$_2$EMISSION* during the study period. By contrast, the GFC in 2008 and 2009 did not cause any structural change in the nonlinear relationship between the *lnGDP* and *lnCO$_2$EMISSION* during the study period.

(ii) To evaluate the effects of the mutation point problem, the Ramsey Regression Equation Specification Error Test (RESET) was performed with an *F*-test (Table 2) (Ramsey, 1974; Long and Bollen, 1993). If the null hypothesis that “all predictive vector coefficients are zero” is rejected, the models present misspecification. According to the results of the Ramsey RESET test, the *p* value of the *F*-statistics at five breakpoint in Table 2 were greater than the 5% significant level. Thus, the null hypothesis that “no important variables are missing in the models” is verified. To confirm the stability of the model parameters in Table 2, the methods described in the following subtopic were used to detect the existence of singular data points in the mean or mean square deviation of the time sequence.

Recursive residual

Cumulative sum and cumulative sum squared

In general, cumulative sum (CUSUM) and CUSUM squared (CUSUM-sq) tests can be used to examine the stability and constancy of the SUR-OLS result. Figure 1 indicates that the CUSUM curve is within two critical straight lines and does not exceed the upper and lower bounds.

Thus, the parameters of the research models were stable. Figure 2 indicates that the CUSUM-sq curve is within two critical straight lines and does not exceed the range, which again proved that the parameters of the research models were stable (Macneill, 1978; Tao et al., 2018).

One-step forecasting

Figure 3 indicates that before 1998, the recursive residuals fell outside the range of two standard deviations (two dashed lines). The recursive residuals in 1997 and 2013 were also outside the range of two standard deviations (two dotted lines). In particular, in 1997, the "original hypothesis of constant parameters" was rejected with a probability of less than 13% of the significance level (Figure 3). Therefore, the aforementioned points may be unstable. Although no instability existed in the entire research models, instability existed in individual points.

N-step forecasting

At a 3% significance level in the *N*-step prediction test, the original hypothesis that the parameters are constant was rejected at only one sample point; thus, the number of sample points at which the original hypothesis was rejected in the *N*-step prediction test was less than that in the one-step prediction test. Rejection of the original hypothesis at a sample point was found for 1997 in both the aforementioned tests. This time frame coincides with the Asian financial turmoil. Figures 1–4 display the surprisingly singular relationship between $lnCO_2$ and *lnGDP* in 1997. The results in Figures 3 and 4 are in agreement with those of Liu et al. (2019). In summary, the Asian financial crisis from 1997 to 1999 caused a sudden change in China's carbon emissions. Although China did not devalue the RMB from 1997 to 1999, its total exports increased during this period.

According to statistics from the National Bureau of Statistics of China and the IEA. Based on constant 2010 USD and calculated in billions of dollars, in 1997, 1998 and 1999, China's GDP was USD1776 billion, USD1915 billion and USD2062 billion, respectively; thus, China maintained stable economic growth from 1997 to 1999.

According to the statistics of the IEA, CO_2 emissions in China increased from 2926 metric tons in 1997 to 3021 metric tons in 1998 but decreased to 2921 metric tons in 1999. Thus, our research indicates that China's GDP and CO_2 emissions changed abruptly from 1997 to 1999. Although the overall model expressed in Equation 7 is stable, the Asian financial crisis caused a structural transformation in the nonlinear relationship between CO_2 emissions and GDP from 1997 to 1999 (Figures 3 and 4). In addition, according to the IEA, the total coal consumption of China in 1996, 1997, 1998, and 1999 was 303915, 298241, 301016, and 258717 ktoe, respectively (Figure 5). Surprisingly, in 1999, the coal consumption of all industries declined significantly compared with their coal consumption in 1998. In particular, the consumption of industrial coal decreased from 230,137 ktoe in 1998 to 190,946 ktoe in 1999 [decrease of 39,191 ktoe (17.03%)]. The decrease in coal consumption may be the main reason for the change in the nonlinear relationship between GDP and CO_2. The Asian financial crisis from 1997 to 1999 significantly affected China's coal consumption structure; however, this effect did not cause economic growth to slow down and exports to decrease from 1997 to 1999. The abrupt decrease in coal demand reflects a sharp decline in CO_2 emissions during this period, especially in 1999. To the best of our knowledge, no study has analyzed the aforementioned phenomenon from the perspective of economic theory or empirical analysis.

A comparison of the Asian financial crisis from 1997 to 1999 with the GFC in the United States from 2008 to 2009 indicated that the Asian financial crisis caused a structural change in the nonlinear relationship between $lnCO_2EMISSIONS$ and *lnGDP* from 1997 to 1999. Moreover, the abrupt reduction in the coal consumption of the industrial sector in 1999 caused a structural transformation in the nonlinear relationship between *lnGDP* and $lnCO_2EMISSION$.

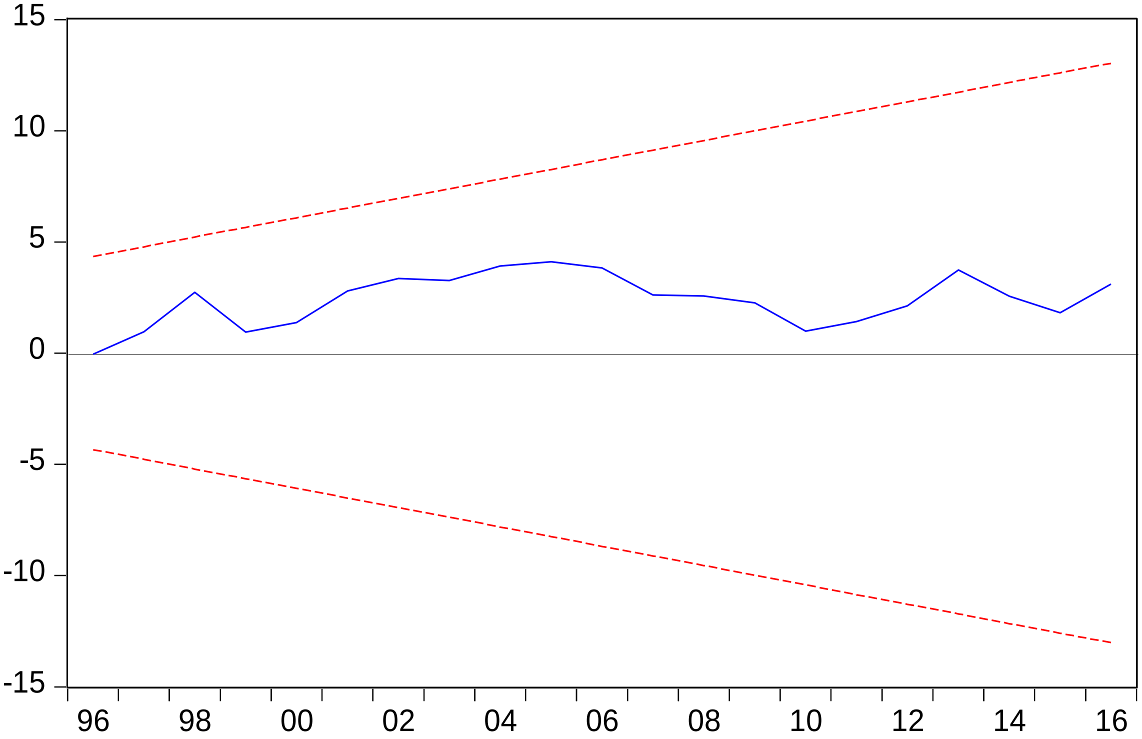

Figure 1. CUSUM diagnostics.

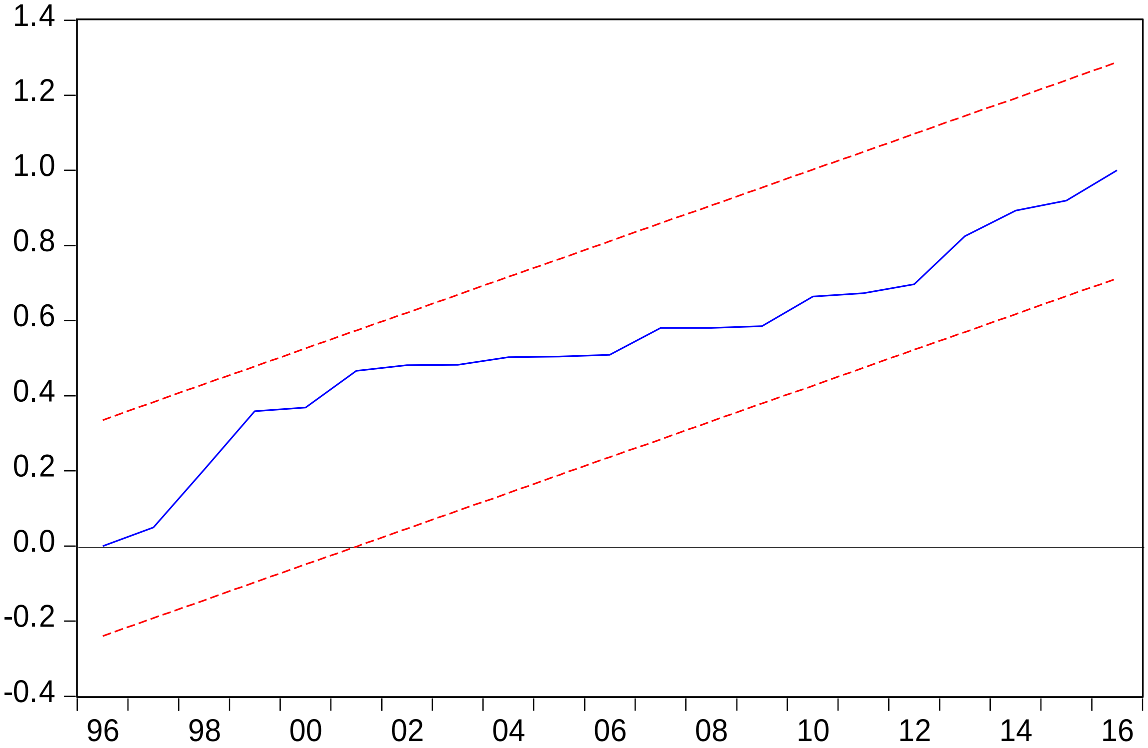

Figure 2. CUSUM of square diagnostics.

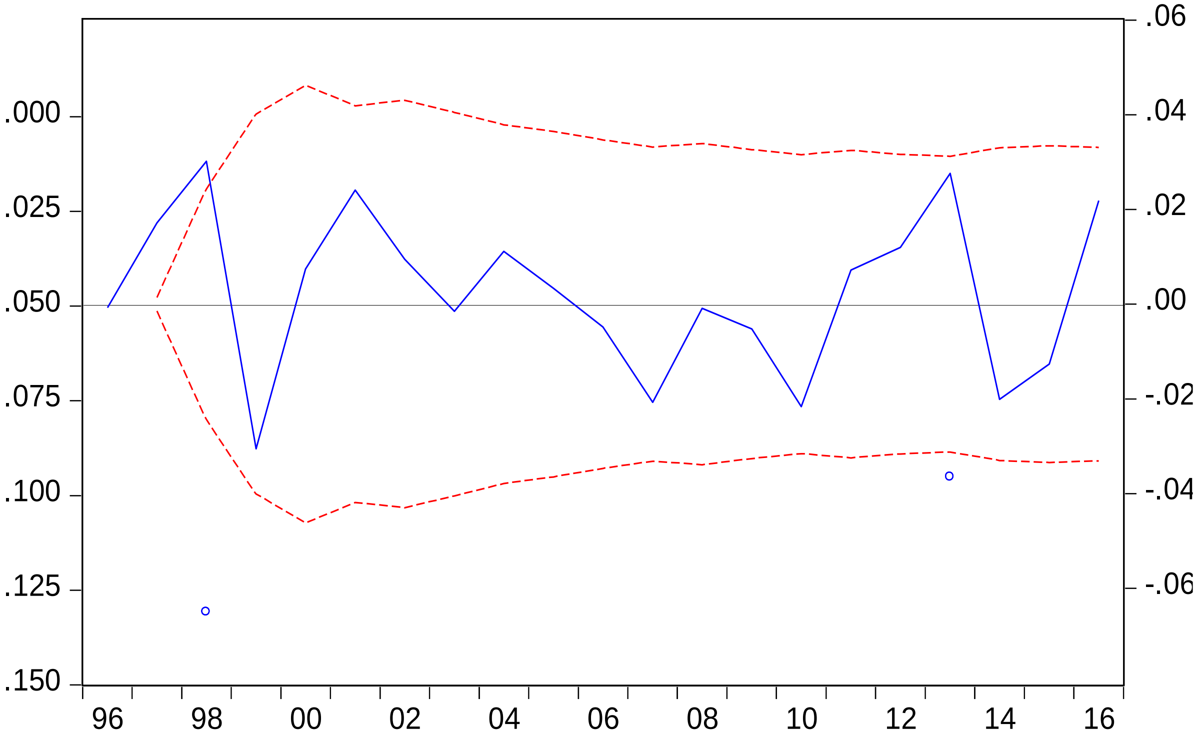

Figure 3. One- step forecast test.

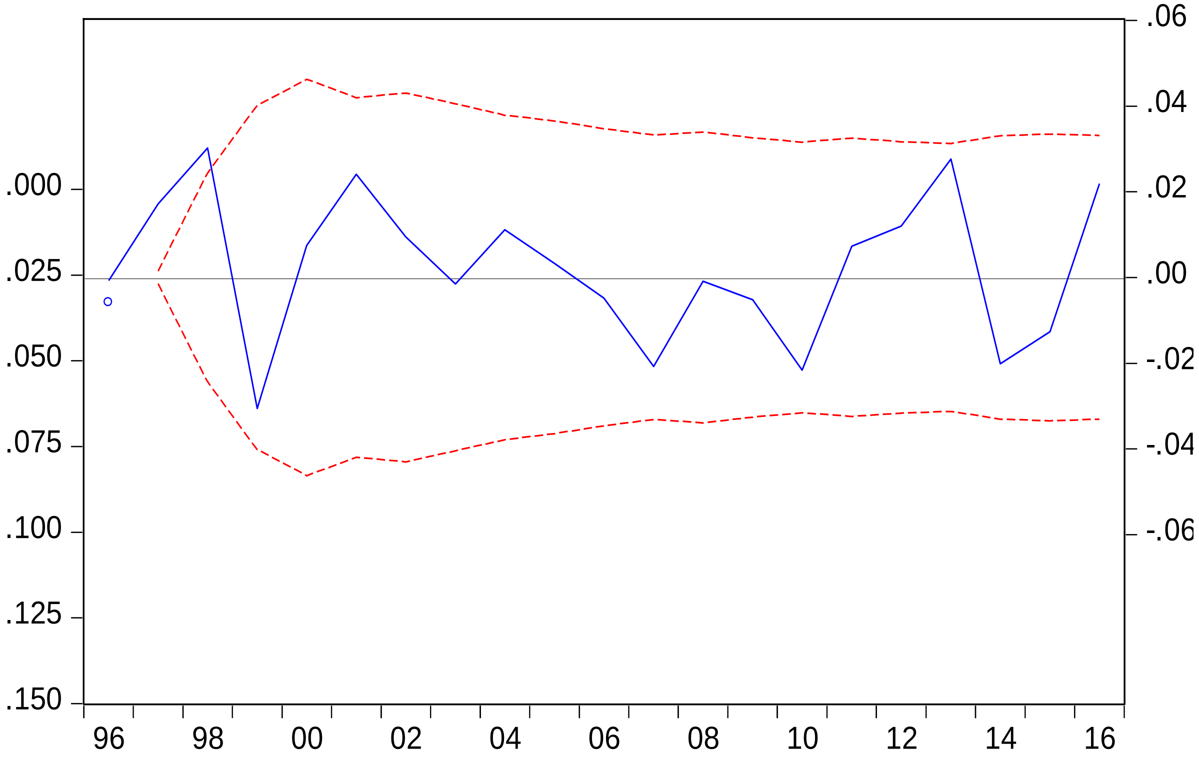

Figure 4. N- step forecast test.

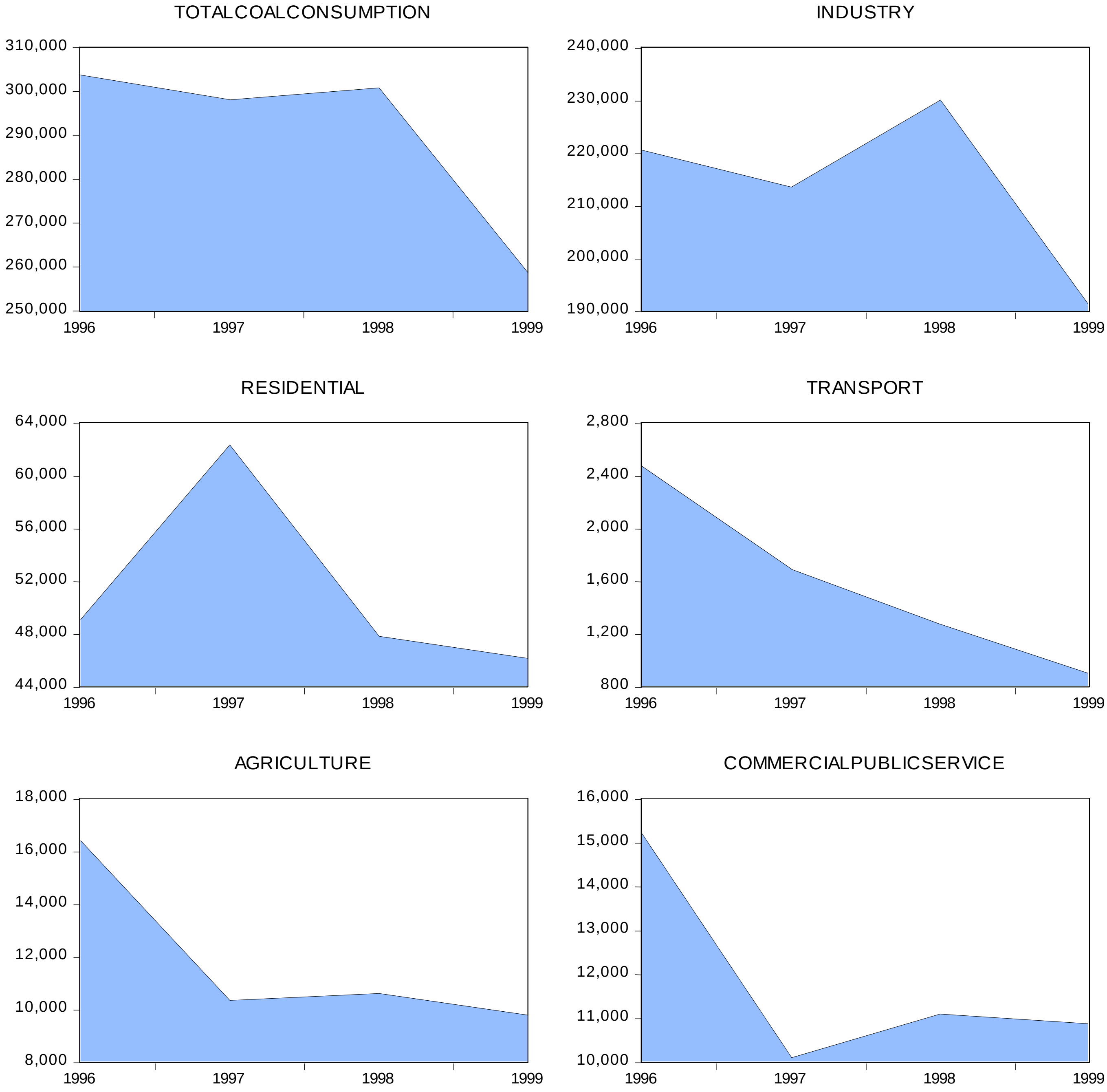

Figure 5. Total coal consumption and final coal consumption by industry, China, 1996-1999.

Multiple-breakpoint test

The previous enforcement of the mutation point was based on subjective analysis. We identified the mutation time point in advance and then checked it. Next, we selected a pattern at random by assuming that the mutation point of the time series was completely unknown in advance (Andrews, 2003; Maasoumi et al., 2010; Liddle and Messinis, 2018). We used the RD approach to examine the result. Table 3 reveals the existence of a breakpoint in 1997. We also used the multiple-breakpoint test to analyze the residual value of the breakpoints of $lnCO_2$ and $lnGDP$. Figure 6 depicts the relationship between $lnCO_2$ and $lnGDP$, which changed suddenly around 1997. The line of the residual began to trend upward and steepen after 1997. The results in Figure 6 confirmed the upward

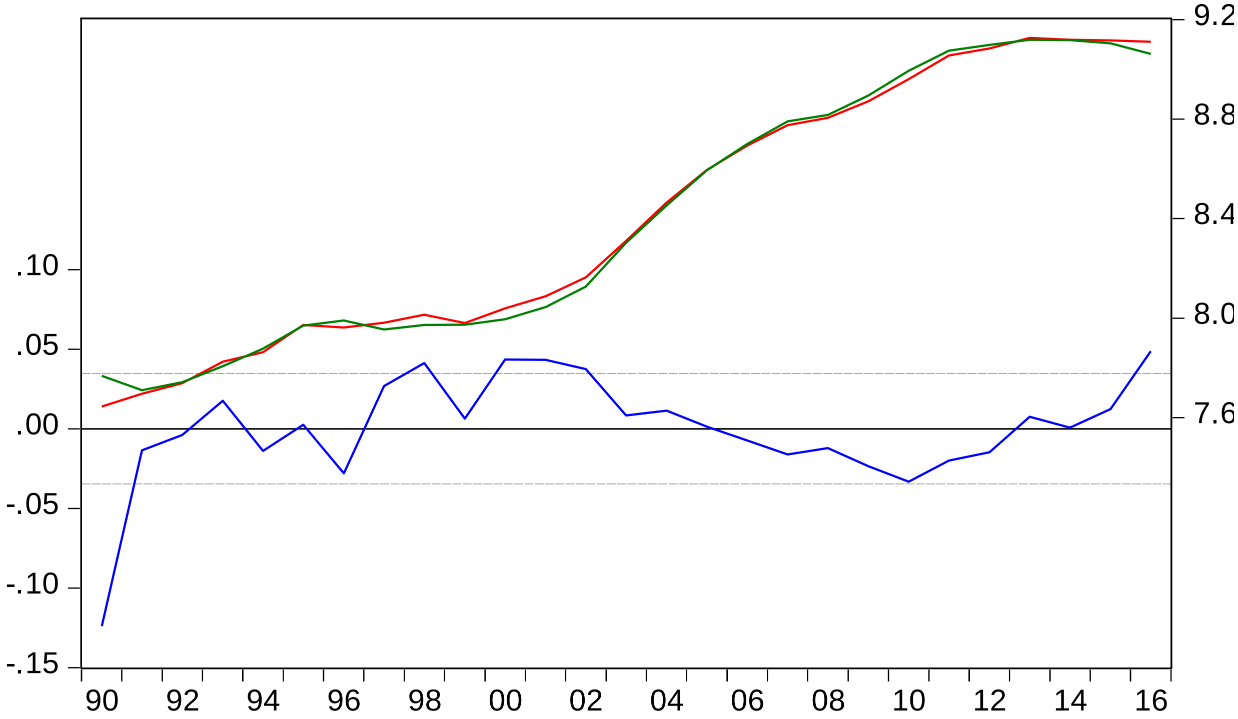

Figure 6. Regression discontinuity test.

Table 3. Implementation of the multiple-breakpoint test (1990–2016).

Method	Sample	Breaking variables	Break test	*F*-statistic	Critical value	Break year
Bai tests (Sequential test all subsets)	1990-2016	C *lnCOALSUPPLY*	0 vs. 1	5.598129	11.47	1997

This table represents the effect of *lnCOALSUPPLY* on *lnCO₂EMISSIONS* in the modeling. The breaking variable is *lnCOALSUPPLY*, where * represents a significance level of 0.05. The Bai–Perron critical value (Bai and Perron, 2003) the set of critical values available with other values of trimming parameterεto enable proper empirical applications. It provides response surface regressions valid for a wide range of parameters. Hence, in the table, we allow the error distributions to differ across breaks in the multiple-breakpoint test.

tendency of this line after 1997.

Turning point predictions and results

In the previous analysis, we used the Chow test. The *p* value in Table 2 indicates that the Asian financial crisis in 1997–1999 caused structural changes in the nonlinear relationship between *lnGDP* and *lnCO*$_2$ emissions during the aforementioned period. We used multiple breakpoints to analyze *lnCO*$_2$ and *lnGDP*. Figure 6 reveals that a sudden change occurred in the relationship between *lnGDP* and *lnCO*$_2$ emissions around 1997.

According to the aforementioned analysis, 1998 was considered as the dividing point, and the SUR-OLS method was used to re-examine whether a Kuznets curve relationship existed between *lnCO*$_2$ and *lnGDP* from 1999 to 2016. The nonexistence of a Kuznets curve indicates that with economic growth, pollution emissions would increase and the environment would continue to be damaged. However, if the current GDP is to the left of the turning point of the Kuznets curve, we can calculate the time required to reach the turning point of the Kuznets curve.

To the best of our knowledge, no studies have discussed the aforementioned problem. China is the world's second-largest economy. Therefore, exploring China's carbon emissions and economic growth is important. We used a subjective mutation and randomized field examination combined with a structural model of carbon emissions and relevant variables to explore the aforementioned problem.

This study is the first to combine EKC theory and

Table 4. Environmental degradation cost: SUR-OLS (1999–2016).

Independent variable	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**	**Model 8 (II)**
lnGDP	6.808652* (9.321685)	**7.519302*** **(10.12352)**	**0.706334** **(1.472951)**	**3.017924*** **(6.727749)**	6.967645* (9.241558)	3.397199* (2.610475)	8.180981* (9.633806)	2.378408* (4.776017)
(lnGDP)^2	-0.357389* (-8.224230)	**-0.375516*** **(-9.366518)**	**-0.030490** **(-1.161259)**	**-0.114323*** **(-4.079663)**	-0.365299* (-8.252886)	-0.164447** (-2.221962)	-0.451602* (-9.259889)	-0.080824* (-2.809261)
lnPOPULATION		**-7.080153***** **(-2.055102)**						
lnCOALSUPPLY			**0.748784*** **(14.15108)**					
ln(TPES//GDP)				**1.042311*** **(10.60919)**				0.928376* (8.165865)
TPES/POPULATION					**-0.027388** **(-0.713751)**			-0.035982** (-2.545274)
lnEMISSIONFEELEVY						0.199960** (2.594363)		0.087434** (2.282333)
lnVEHICLEPURCHASETAX							0.144742** (2.259542)	
AR(1)	1.976693* (16.59676)	1.699435* (13.24160)	1.979498* (22.69073)	1.979059* (14.61920)	1.984867* (31.44552)	1.976101* (13.50546)	0.849335** (2.739147)	0.651614*** (2.033400)
AR(2)	-0.986386* (-8.540894)	-0.824515* (-5.643744)	-0.985665* (-11.49052)	-0.987465* (-7.655694)	-0.993592* (-16.10912)	-0.986149* (-6.941688)	–	–
E-Wstat	0.789588	0.801032	1.329335	1.866585	0.784597	0.928269	0.883543	1.599692
Adjusted-R^2	0.991077	0.992256	0.999211	0.998682	0.990702	0.993424	0.990605	0.998928
γ*=(lnGDP)* (inflection point of KC)	9.525547	10.011959	11.583043	13.199111	9.536906	10.329160	9.057733	14.713500

This table presents the variables in the logarithmic form. The symbols *, **, and *** represent significance levels of 1, 5, and 10%. The numbers in the brackets are the *t*-statistics of the estimated parameters. The logarithm of GDP in 2016 was 9.159573. The data regarding CO_2 emissions, population, GDP, TPES, and coal supply were obtained from the IEA. The vehicle purchase tax and pollution fee levy data were obtained from the National Bureau of Statistics of China.

the RD approach to perform empirical analysis for observing the structural change in the relationship between $lnCO_2$ and *lnGDP*.

- **Case 1:** In model 1 of Table 4, we divided the sample into two intervals according to the aforementioned breakpoint estimates. The influences of *lnGDP* and (*lnGDP*)^2 on $lnCO_2$ were observed without considering the influence of other parameters. The obtained results indicated that the autoregressive (AR) model, AR (1) and AR (2) coefficients passed the 5% significance test, which indicated that an inverse U-shaped correlation existed between environmental degradation cost and GDP. Thus, a Kuznets inflection point existed between China's GDP growth and CO_2 emissions during the study period (1999–2016). By using model 1 in Table 4, we calculated the inflection point of the quadratic curve to be 9.525547. Based on constant 2010 USD and calculated in billions of dollars, China's GDP in 2016 is USD9505 billion, the logarithmic value of 9505 is 9.159573. When neglecting the effects of other policies, Equation 6 implies that the current economic development of China has not reached but is approaching the inflection point of the Kuznets curve (Figure 7). **Case 2:** Model 3 in Table 4 was obtained by adding

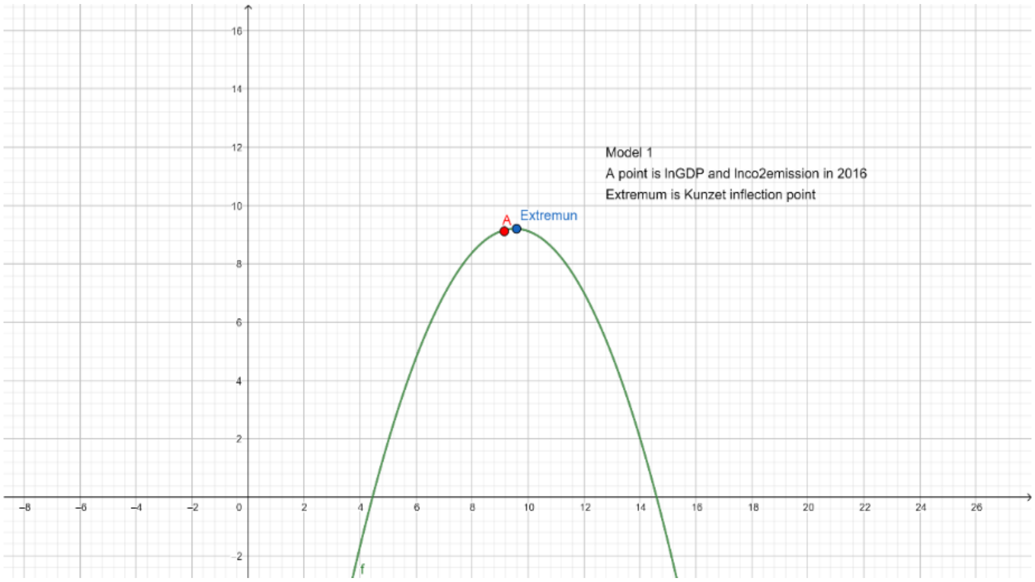

Figure 7. Implementation of environmental degradation cost - SUR-OLS, 1999-2016.
Remarks: The figure is taken from Table 4 in Model 1.

the variable *lnCOALSUPPLY* to model 1 of Table 4. The corresponding regression coefficient was 0.748784, which passed the 1% significance level. The aforementioned coefficient was positive, which indicates that an increase in coal consumption leads to an increase in the environmental degradation cost. When using model 3 in Table 4, the inflection point of the EKC was obtained as 11.583043. The results of model 3 in Table 4 indicate that the time of incurring environmental degradation costs is prolonged after incorporating coal supply parameters. Model 3 in Table 4 provided a higher EKC turning point than model 1 of Table 4. The difference in the EKC turning points of the two models was 2.057. In addition, when using model 8 in Table 4 after incorporating the relevant variables, the time for environmental degradation costs was delayed by 5.187953 years compared with that obtained with model 1 of Table 4. If average economic growth rate data are available, the time required for a country to reach the EKC turning point can be calculated using Equations 6 and 8. In summary, the regression coefficient of *lnEMISSIONFEELEVY* was positive for models 6 and 8 in Table 4, which indicates that emission fee levy increases the cost of environmental degradation. The aforementioned finding may be the reason why China replaced its emission fee levy with an environmental protection tax in 2018.

DISCUSSION AND CONCLUSIONS

Although EKC theory has been widely used to describe the relationship between economic growth and carbon emissions, limited knowledge exists regarding its empirical validity. To check the robustness of our results, we used data from the IEA, National Bureau of Statistics of China, and China Statistical Yearbook. By using EKC theory combined with the RD approach, we empirically examined the relationship between economic growth and carbon emissions. We performed some empirical tests, including the unit root and ARDL bounds tests, on a Chinese data sample for 1990–2016. Regress our dependent variables on the performance alone and include control variables step wise (Wang et al., 2019). To investigate the robustness of our results, we ran numerous regressions based on the SUR-OLS specification and used the Chow test to redefine the breakpoint in advance. Unlike the majority of relevant previous studies, this study used both subjective mutation and randomized field examination combined with a structural model of carbon emissions and relevant running variables to explore the aforementioned relationship. The breakpoint time of the Chow test was obtained in advance. To confirm the robustness of our results. We assumed that this mutation point pattern was selected at random, and that the mutation point of the time series was completely unknown in advance. This study is the first to combine EKC theory and the RD approach to perform empirical analysis for observing the structural change in the relationship between economic growth and carbon emissions. For various regressions reported in this study, a U-shaped relationship was obtained between the cost of environmental degradation and *lnGDP* for China when the effects of government policies and the influence of other parameters were not considered and when only the effects of *lnGDP* and (*lnGDP*)^2 on *lnCO$_2$* were considered. This result indicated that a Kuznets inflection point did not exist between China's *lnGDP* growth and *lnCO$_2$* emissions during 1990–2016. However, the Chow test and RD test results indicated that regardless of the effect of other policies, China's current economic development has not yet reached but is approaching the turning point of the Kuznets curve. Numerous regressions reported in this study indicated that a statistically significant and inverse U-shaped relationship existed between economic growth and carbon emissions during 1990–2016 in China. Another important finding of our analysis is that although the overall structural model was stable when using Equation 10, the Asian financial crisis caused a structural change in the nonlinear relationship between *lnCO2* and *lnGDP* from 1997 to 1999. The substantial reduction in the coal demand in 1999 played an important role in the structural change in the nonlinear correlation between *lnGDP* and *lnCO$_2$*. However, the GFC of 2008–2009 did not lead to structural changes in the nonlinear relationship between *lnGDP* and *lnCO$_2$* emissions during 2008–2009, which indicated that CO$_2$ emissions and economic growth are not necessarily linked. China has the highest population in the world, and its TPES increased every year from 1990 to 2016, in which the TPES was 2958 Mtoe. However, during the past 4 years, CO$_2$ emissions in China have gradually decreased even though GDP has increased. As per the UNFCCC 2009 Copenhagen Accord, China agreed to voluntarily reduce its carbon emissions by 40 to 45% in 2020 compared with its carbon emissions in 2005. Data from the IEA indicated that the ratio of CO$_2$ to GDP was 1.5 in 2005 and 0.9 in 2016. Thus, China's carbon emissions decreased by 40% from 2005 to 2016. Consequently, China achieved the goal of the 2009 Copenhagen Agreement 4 years in advance. We extend our results to examine the effect of emission fee levy on the cost of environmental degradation. A positive relationship was obtained between emission fee levy and CO$_2$ emissions, which confirmed our hypothesis. This finding may be one of the reasons why the Chinese government has implemented environment protection taxes instead of penalties in the environmental regulations since 2018. Finland, Sweden, Norway, and Denmark have imposed carbon taxes since 1990 (Piciu and Trică, 2012). The effectiveness of the environmental protection tax implemented in China since 2018, is an important topic that can be examined in future research. Many studies have indicated that during the 1997 Asian financial crisis, China maintained stable economic growth, the RMB did not depreciate, and Chinese exports continued to increase. However, to the best of our knowledge, no study has indicated that China's coal consumption dramatically decreased during the Asian financial crisis. Moreover, China's CO$_2$ emissions decreased from 3.021 billion tons in 1998 to 2.92 billion tons in 1999. However, its GDP increased from USD1776 billion in 1997 to USD1915 billion in 1998 and USD2062 billion in 1999. Thus, during the 1997 Asian financial crisis, China's GDP exhibited sustainable growth. Finally, our empirical results indicated that the Asian financial crisis caused the alternation of the inverse U-shaped relationship between China's economic growth and CO$_2$ emissions, which is a major finding of this study.

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