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Environmental Kuznets curve, balanced growth, and influencing factors: evidence from economic development in China

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Abstract

Purpose – The aggregate index and per capita index have different meanings for some countries or regions. CO_2 emissions per capita matters for China because of its huge population. Therefore, this study aims to deepen the understanding of Kuznets curve from the perspective of CO_2 emissions per capita. In this study, mathematical formulas will be derived and verified.

Design/methodology/approach – First, this study verified the existing problems with the environmental Kuznets curve (EKC) through multiple regression. Second, this study developed a theoretical derivation with the Solow model and balanced growth and explained the underlying principles of the EKC's shape. Finally, this study quantitatively analyzed the influencing factors.

Findings – The CO_2 emission per capita is related to the per capita GDP, nonfossil energy and total factor productivity (TFP). Empirical results support the EKC hypothesis. When the proportion of nonfossil and TFP increase by 1%, the per capita CO_2 decrease by 0.041 t and 1.79 t, respectively. The growth rate of CO_2 emissions per capita is determined by the difference between the growth rate of output per capita and the sum of efficiency and structural growth rates. To achieve the CO_2 emission intensity target and economic growth target, the growth rate of per capita CO_2 emissions must fall within the range of $[-0.92\%, 6.1\%]$.

Originality/value – Inspired by the EKC and balanced growth, this study investigated the relationships between China's environmental variables (empirical analysis) and developed a theoretical background (macro-theoretical derivation) through formula-based derivation, the results of which are universally valuable and provide policymakers with a newly integrated view of emission reduction and balanced development to address the challenges associated with climate change caused by energy.

Keywords Environmental Kuznets curve (EKC), CO_2 emissions, Influencing factors, Balanced growth

Paper type Research paper

1. Introduction

Global academic researchers and policymakers are aware that climate change is seriously threatening human sustainability (Ikeme, 2003; Owusu and Asumadu-Sarkodie, 2016; Phuong *et al.*, 2019; Sim and Kim, 2019; Wang *et al.*, 2018, 2020b; Wu *et al.*, 2016). From the United Nations Framework Convention on Climate Change and the Kyoto Protocol to the Paris Agreement, human beings have recently been attempting to solve the climate change

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crisis and striving for the sustainability of humanity. Due to greenhouse gas emissions, especially CO_2 emissions, the world's average temperature has increased by 0.17°C every decade since 1970 (Rahman *et al.*, 2020b). In 1987, the World Commission on Environment and Development (WCED) issued a report entitled "Our common future" (Lebel and Kane, 1989) that formally adopted the concept of sustainable development to meet the needs of the contemporary generation without harming the needs of future generations. In 1992, the Conference on Environment and Development, held in Rio de Janeiro, Brazil, approved the Rio Declaration, Agenda 21 and other important documents, and gradually formed the concept of sustainable development. Subsequently, the Chinese government formulated the white paper on population, resources, environment and development in the 21st century, which, for the first time, incorporated a sustainable development strategy into China's long-term plan for economic and social development. At the 15th National Congress of the Communist Party of China in 1997, sustainable development was identified as a strategy that must be implemented in China's modernization process. In 2002, the 16th National Congress of the Communist Party of China identified "continuously enhancing the capacity for sustainable development" as one of its goals for comprehensively building a moderately prosperous society. According to a report of the International Bank for Reconstruction and Development, with the development of the world economy and the increase of per capita income, the demand for a high-quality environment is certain to increase. Therefore, reducing the impacts of climate change and fully predicting climate are the most important issues for sustainable development.

Climate change is usually caused by CO_2 emissions and other pollutants such as SO_2, suspended particles and NO_x. China's industrialization process has not only resulted in high economic growth rate but higher consumption of many energy resources, significantly increasing the emissions of CO_2 and other pollutants increase. Since the implementation of reform and opening-up in 1978 to achieve economic growth and social development (Li and Lin, 2015), China has become the world's second largest economy after the USA (Oliver *et al.*, 2013). China is also the world's largest emitter of CO_2, creating extremely serious challenges for the sustainable development of not only itself but also the world. These emissions cause disaster events, such as global warming, ozonated completion, a loss of biodiversity, acid rain, deforestation, water pollution, marine pollution and solid waste pollution (Gu *et al.*, 2013; Shi *et al.*, 2019). At present, China is making efforts to reduce CO_2 emissions, a major component of greenhouse gas emissions. Identifying the factors affecting CO_2 emissions is crucial for developing policies to reduce such emissions. Therefore, an in-depth study of the affecting factors of CO_2 emissions has become a research focus.

Consensus has been reached that economic growth leads to environmental degradation and an increase in carbon dioxide emissions. In the earlier phases of economic growth, the environment deteriorated rapidly because people had little understanding of potential environmental problems, and no advanced technology was available to tackle these problems. To maintain economic growth, environmental pollution was often ignored. With increases in the level of per capita income and welfare, people have a deeper understanding of the environment. In response, the pace of deterioration has slowed and the demand for a better environment has gradually dominated the discussions. Therefore, when per capita income reaches a particular level, the influence of economic growth on the environment changes from negative to positive (Panayotou, 1993). In environmental economics literature, this hypothesized inverted U-shaped association between economic and environment status is referred as the environmental Kuznets curve (EKC), named after Simon Kuznets, who specified an inverse U-shape curve for describing the association between income disparity and economic growth. The EKC hypothesis has been widely used by scholars to test the association between variables of economic growth and environmental pollution and has become a guiding framework to identify the influencing factors of CO_2 emissions.

The function of the EKC can be summarized from two perspectives. First, it provides researchers with a framework to examine the association between environmental variables and other variables, such as per capita income. The latest research shows that the application of this method is not limited to environmental problems but also affects other fields. Second, it provides a reference basis for policymakers to formulate environmental policies. EKC, however, is mainly fitted with time-series data and subjective experience plays an important role in its assessment. Notably, few scholars have studied the reasons behind its shape.

Although some scholars conducted some exploratory studies on the relationship between per capita CO_2 emissions and per capita GDP in an attempt to uncover the causal relationship between the two variables, some issues remain to be clarified. Questions such as why the EKC is inverse U-shaped and whether other factors have a crucial impact on the EKC are worthy of further study. In this study, we aimed to investigate the impact of factors other than per capita GDP on per capita CO_2 emissions based on verifying the shape of China's EKC. The impact mechanism and quantitative association of per capita GDP, the proportion of nonfossil fuels and total factor productivity (TFP), and per capita CO_2 emissions were deeply explored; the results enrich our understanding of the EKC and provide decision-making support for China's climate change mitigation policies.

Compared with other studies, the innovations are mainly reflected in the following aspects. First, the factors that influence CO_2 emissions are complicated, and varying conclusions may be drawn from different regions and different stages of development. Studies have examined the factors from various perspectives with different technologies, but few were conducted from the perspective of per capita growth rate. The reason we chose the per capita growth rate is that although China's economic development is rapid and its energy consumption is huge, China's population is large. For China, its per capita and total amount indicators will be different or even opposite. Second, in addition to the growth rate of GDP per capita, we introduced the TFP, the proportion of nonfossil energy, and emission structure coefficients as new influencing indicators. No research, to the best of our knowledge, has conducted this type of research. Finally, based on the Solow model and balanced growth, for the first time, we theoretically studied the underlying causes. This method is universally significant for analyzing the reasons for CO_2 emissions per capita and could be used as an analysis tool for any region or country. In addition, the TFP, as an index of economic activity or GDP in the past, is included in the index to measure the change rate of per capita CO_2 emission. The TFP was used here for the first time to test the validity of the EKC hypothesis.

2. Literature review

The number of studies on the factors affecting CO_2 emissions has been growing, including economic growth (AhAtil *et al.*, 2019; Shi *et al.*, 2019), energy use (AhAtil *et al.*, 2019; Khan *et al.*, 2019), urbanization (Ali *et al.*, 2019; Khan *et al.*, 2019; Li and Zhou, 2019; Shi *et al.*, 2019; Wang *et al.*, 2019b), regional agglomeration (Wang *et al.*, 2019a), industrialization, industry structure, income level (Qu *et al.*, 2019; Shafik and Bandyopadhyay, 1992), carbon tax (Chyong *et al.*, 2020), energy intensity (Wang *et al.*, 2019a), renewable energy (Charfeddine and Kahia, 2019; Maji, 2019), technological development (Khan *et al.*, 2019; Wang *et al.*, 2019c), trade (Khan *et al.*, 2019; Wu *et al.*, 2019), finance (AhAtil *et al.*, 2019; Charfeddine and Kahia, 2019; Khan *et al.*, 2019; Le *et al.*, 2020), population (Li and Zhou, 2019; Shi *et al.*, 2019) and corruption (Apergis and Ozturk, 2015; Ozturk and Al-Mulali, 2015). Various driver analysis models were used in these studies. Typical models include input-output models (Lin and Xie, 2016; Xie and Zhu, 2020; Yan *et al.*, 2016; Zhang *et al.*, 2017), regressive models (AhAtil *et al.*, 2019; Charfeddine and Kahia, 2019; Khan *et al.*, 2019; Wang *et al.*, 2019c), the computable general equilibrium model (Wu *et al.*, 2019), the IPAT (I = human impact, P = population, A = affluence, T = technology) model (Chang *et al.*, 2018; Dong *et al.*, 2016; Kumar and Stauvermann, 2019; Qu *et al.*, 2017; Song *et al.*, 2018; Tomkiewicz, 2010), the Stochastic Impacts by Regression on Population, Affluence and Technology model (Duan *et al.*, 2020; Shao *et al.*, 2010; Tang *et al.*, 2019), the Laspeyres method (Li *et al.*, 2017; Shang *et al.*, 2016), the logarithmic mean Divisia index (LMDI) method (Wen and Li, 2020; Yang *et al.*, 2020; Zhang *et al.*, 2020), clustering analysis (Wang *et al.*, 2020a), system generalized method of movements (AhAtil *et al.*, 2019) and the EKC model (Al-Mulali *et al.*, 2016; Feng and Ye, 2012; Liu *et al.*, 2018; Rahman *et al.*, 2020a, 2020c; Yang and Xie, 2015).

Many studies showed that economic activities and technology are the most important factors affecting CO_2 emissions from positive and negative perspectives, respectively. Charfeddine and Kahia (2019) surveyed the role of the new energy and financial development in the Middle East and North Africa region and argued that new energy and financial development have insufficient informative power to explain CO_2 emissions and economic growth. Wang *et al.* (2019c) investigated the impact of technological progress in China with panel quantile regression and drew the conclusion that the impact of technological progress on CO_2 emissions varies across different economic sectors, and technological progress exerts different effects on different emitters for moderating energy intensity. Using the data from 149 countries from 1960 to 1990, Shafik and Bandyopadhyay (1992) observed a positive association between CO_2 emissions and income per capita. Li and Li (2011) supported an inverse U-shaped curve association between economic growth and CO_2 emissions. Using the LMDI method and Chinese data from 1957 to 2000, Wang *et al.* (2005) argued that energy intensity, at a technical level, has an obvious effect on CO_2 emission reductions, whereas economic growth leads to an increase in CO_2 emissions. Using the provincial data for China from 1997 to 2007, Wei and Yang (2010) observed that economic growth, industrialization and trade liberalization can promote CO_2 emissions, whereas technological progress can reduce CO_2 emissions.

Social factors such as population, urbanization, trade and energy consumption structures also have a substantial influence on CO_2 emissions. With the Lotka–Volterra model, Puliafito *et al.* (2008) examined the association between populations, GDP, energy and CO_2 emissions. The results showed that the population scale is the main affecting factor, and population mix also influences CO_2 emissions. Martínez-Zarzoso and Maruotti (2011) conducted an empirical study on the impact of the level of urbanization on carbon dioxide in undeveloped countries and concluded that the relationship between these two variables is an inverted U-curve. Knapp and Mookerjee (1996) argued that according to the Granger causality results, no long-standing cointegration association exists between population size and carbon dioxide emissions, but global population growth increases the CO_2 emissions. Siddiqi (2000) illustrated that increases in CO_2 emissions correspond to the increases in energy consumption. Shi *et al.* (2019) reported that influencing factors of CO_2 emissions vary substantially across prefectures and provinces in China, and energy policies should proceed based on local conditions. Wang *et al.* (2019a) found that energy-intensive industries in China will achieve their CO_2 peak before 2030, and regional convergence can provide a large potential for CO_2 emission reductions. The impacts of China's demographic structures on CO_2 emissions were assessed by Li and Zhou (2019), and the dependency ratio and average household size were clarified to have negative effects on CO_2 emissions.

Grossman and Krueger (1991) examined the association between the economy and the environment and found a resemblance to EKC. They proved that the association of income per capita and CO_2 emissions is linear; nevertheless, the impact of the quadratic form on CO_2 emissions is negative, which verifies the EKC hypothesis. Following Grossman and Krueger, numerous scholars have tested the EKC hypothesis with a wide range of methodologies in diverse contexts. Different data sets and different pollution indicators (SO_2 and NO_x) have been employed, but these studies have yielded inconclusive, inconsistent, and even contradictory empirical findings. Some papers support the validity of the EKC hypothesis (Alam *et al.*, 2016; Apergis, 2016; Apergis and Ozturk, 2015; Li *et al.*, 2016), but others reject it (Adu and Denkyirah, 2018; Al-Mulali *et al.*, 2015; Amri, 2017; Antonakakis *et al.*, 2017; Fodha and Zaghdoud, 2010; Jebli and Youssef, 2015; Jebli *et al.*, 2016; Ozturk and Al-Mulali, 2015). The research objectives of these papers include both a specific country and a group of countries and the data used include both time series data and panel data.

Although there are arguments about the validity of the EKC, the underlying reasons can be ascribed to the choices of development contexts, time cycles, methods and explanatory or control variables. These additional or control variables include energy consumption (Alam *et al.*, 2016; Amri, 2017; Antonakakis *et al.*, 2017; Apergis and Payne, 2010), trade (Adu and Denkyirah, 2018; Al-Mulali *et al.*, 2016; Jebli *et al.*, 2016; Li *et al.*, 2016), population (Adu and Denkyirah, 2018; Alam *et al.*, 2016; Li *et al.*, 2016) and urbanization (Li *et al.*, 2016), but no one has yet investigated the impact of the fraction of nonfossil energy and TFP on the variation rate of CO_2 emissions per capita. Besides economic growth, the fraction of nonfossil consumption and TFP also has a significant impact on CO_2 emissions. In the process of realizing a high growth rate through industrialization, China has consumed a large quantity of fossil fuels, especially coal, and the country's CO_2 emissions have increased rapidly. The consumption of natural resources and the increasing demand for traditional energy will inevitably force decision-makers to find alternative energy sources (Toklu, 2013). Due to global warming, renewable energy (e.g. biomass energy, geothermal energy, water power, photovoltaic power generation and wind energy) and new energy (such as nuclear energy) have been widely used alternative to fossil fuels, and are thought to be solution to the problems of energy security and climate change (Menyah and Wolde-Rufael, 2010). Several countries have turned to the exploration and development of renewable energy to reduce their dependence on fossil fuels and environmental pollution and to mitigate the impacts of oil price fluctuations (Bölük and Mert, 2014). The use of renewable energy is an imperative method for reducing CO_2 emissions, but its mechanisms and the degree of its impact on the environment are worthy of further study.

Chinese scholars are deeply involved in the study of EKC, and their research classifications are summarized as follows. The first category, verifying the existence of China's EKC. Feng and Ye (2012) claimed that there is an EKC in eastern China but not in the western and central regions. The proportion of secondary industries in the total GDP of China has a positive influence on CO_2 emissions. Yang and Xie (2015) found that China's EKC assumes an inverse N-shape and that the decisive factor affecting the shape of the EKC is economic growth. In summary, due to the differences in the selection of research objects, environmental variables, and the starting points for time series data, the conclusions on the existence and shape of the EKC are inconsistent. The second category, predicting the inflection point of EKC and its influencing factors. Lin and Jiang (2009) projected that the per capita income corresponding to the theoretical inflection of China's CO_2 EKC will be about 37,170 CNY around 2020, and in addition to per capita income, energy intensity, industrial mix and energy mix all have substantial effects on CO_2 emissions. Jiang and Yu (2010) observed that the influencing factors at the inflection point of the EKC include the growth of economic scale, economic mix and environmental control factors, but do not offer a mechanism for the effects of these factors. The third category, comparative studies on the EKC between China and other countries. Tang *et al.* (2015) showed that under the continuous growth of the economies of APEC members, CO_2 emissions cannot be guaranteed to decline, and a further promotion of the clean development mechanism is conducive to controlling the total energy consumption and adjusting the energy structure. In summary, existing studies showed that many factors can affect the inflection point of the EKC, but the manifestations of these effects are different.

Overall, many factors influence CO_2 emissions, all of which are complicated; different factors play different roles in different time periods and in different countries or regions. However, for the sustainable development of human beings, scholars continue to conduct in-depth research on CO_2 emissions. New factors are consistently included in the ongoing research, which enriches our knowledge of the key factors affecting CO_2 emissions. As mentioned above, from the per capita growth rate, with the EKC model, Solow model, and balanced growth, we discussed the influencing factors of the per capita CO_2 emission growth rate combined with an empirical analysis and a macro theoretical analysis. The results consider not only the actual situation of China but the universal implications for the world.

3. Methods description and data acquisition

3.1 CO_2 emission estimation

Fossil fuels are primarily responsible for the CO_2 emissions in China. With the same efficiency, coal produces the most CO_2 among all types of fossil fuels, where natural gas produces the least and nonfossil energy produces a negligible amount. With reference to the method for estimating CO_2 in the Intergovernmental Panel on Climate Change (IPCC) Guide (2006), we used equation (1) to estimate China's CO_2 emissions over the years. The CO_2 emissions per capita are the ratio of total CO_2 emissions to the total population:

$$C = \frac{44}{12} \times \sum_{i=1}^{3} E \times w_i \times \eta_i \qquad (1)$$

where C denotes the CO_2 emissions (10,000 metric tons); E denotes the total energy consumption (10,000 metric tons standard coal) in China; w_i represents the proportion of energy type_i in total energy consumption; and η_i is the emission coefficient of energy type_i; According to the IPCC, the CO_2 emission coefficients for coal, oil and natural gas are 0.7559, 0.5857 and 0.4483, respectively.

3.2 EKC model settings

Referring to the existing EKC modeling method, we selected the per capita CO_2 emissions of environmental variables as the explained variable, the per capita income (GDP per capita, 100 million CNY × $10{,}000^{-1}$ people) as the explanatory variable, and used the proportion of nonfossil energy and TFP as the control variables. By assuming that a linear relationship and a quadratic curve relationship exist between per capita CO_2 and per capita GDP and gradually introducing the control variables, Models 1–5 are obtained as follows:

$$y_i = \beta_0 + \beta_1 x_i + u_i \qquad \text{Model 1}$$

$$y_i = \beta_0 + \beta_1 x_i + \beta_2 nc_i + u_i \qquad \text{Model 2}$$

$$y_i = \beta_0 + \beta_1 x_i + \beta_2 x_i^2 + u_i \quad \text{Model 3}$$

$$y_i = \beta_0 + \beta_1 x_i + \beta_2 x_i^2 + \beta_3 nc_i + u_i \quad \text{Model 4}$$

$$y_i = \beta_0 + \beta_1 x_i + \beta_2 x_i^2 + \beta_3 nc_i + \beta_4 A_i + u_i \quad \text{Model 5}$$

where y_i is CO_2 emissions per capita, x_i is per capita GDP, nc_i is the fraction of nonfossil consumption, A_i is TFP, u_i is a random disturbance term and β_i is the parameter to be estimated.

Model 1 presents the linear association model between the CO_2 emissions per capita and GDP per capita; Model 2 provides a linear association between the CO_2 emissions per capita, GDP per capita and the proportion of nonfossil energy; Model 3 is the EKC of China; and Models 4 and 5 are extended models based on Model 3 by introducing the proportion of nonfossil energy consumption and TFP, respectively.

3.3 The growth rate of China's per capita CO_2 emissions under a balanced growth path

Assuming that an economic system is completely market-oriented and that there are representative manufacturers in the economic system. A generalized Cobb–Douglas production function can be used to represent the manufacturer's production process:

$$Y = AK^{\alpha} E^{\beta} L^{1-\alpha-\beta} \tag{2}$$

where Y is the output value of the representative manufacturers; K denotes the capital input; L represents the labor input; E denotes the energy input; A denotes knowledge; and α and β are the elastic coefficients of capital and energy, respectively. Knowledge and labor are exogenous variables, the form of technological progress is Hicks-neutral, and the production function satisfies constant returns to scale.

The CO_2 emission formula is: $C = \frac{44}{12} \times \sum_{i=1}^{3} E \times w_i \times \eta_i$. After identical transformation and substituting the E on the right of equation (2), we obtain the following equation (3):

$$Y = AK^{\alpha} (\frac{C}{M})^{\beta} L^{1-\alpha-\beta} \tag{3}$$

Let $M = \frac{44}{12} \sum_{i=1}^{n} w_i \eta_i$, where M is the structure coefficient of CO_2 emissions. CO_2 emissions are the undesirable output of economic systems and have a strict mapping relationship with energy input. To easily analyze the relationship between per capita CO_2 emissions, we use the CO_2 emissions to replace energy input and introduce emissions to the Cobb–Douglas production function. A mapping relationship between the two variables is applied, rather than using economic causality. Therefore, the dynamic evolution equation of the input factors in the production function can be written as:

$$\dot{K}(t) = sY(t) - \delta K(t) \tag{4}$$

$$\dot{L}(t) = nL(t) \tag{5}$$

$$\dot{A}(t) = gA(t) \tag{6}$$

where δ denotes the capital depreciation rate, s represents the savings rate, and n and g are the growth rate of labor and knowledge, respectively.

Divide both sides of the equation $\dot{K}(t) = sY(t) - \delta K(t)$ by $K(t)$, and the result is:

$$\frac{\dot{K}(t)}{K(t)} = s\frac{Y(t)}{K(t)} - \delta \tag{7}$$

Take the logarithm of equation (7) and then take the derivative with respect to time t:

$$g_{Y/L}(t) = g_A(t) + \alpha g_{K/L}(t) + \beta\big(g_{C/L}(t) - g_M(t)\big) \tag{8}$$

where $g_{Y/L}(t) = \frac{dY(t)/L(t)}{dt}$ is the growth rate of Y/L. Drawing on the concept of balanced growth from the Solow model, all input elements of the balanced growth path increase at a constant rate. To keep the growth rate of K/L unchanged, Y/K must be unchanged, and K/L and Y/L must have the same growth rate. Insert $g_{K/L}(t) = g_{Y/L}(t)$ into equation (8), and the function (relationship) of the growth rate of CO_2 emissions per capita and the growth rate of GDP per capita under a balanced growth path can be obtained:

$$g^{bgp}_{C/L}(t) = \frac{1-\alpha}{\beta} \times g^{bgp}_{Y/L}(t) + g_M - \frac{g}{\beta} \tag{9}$$

Equation (9) indicates that under a balanced growth path, the growth rate of CO_2 emissions per capita is related to the growth rate of the output per capita, the growth rate of the CO_2 emission structure coefficient and the growth rate of knowledge. Among the influencing factors, the growth rate of output per capita and the growth rate of knowledge have been studied in economics, whereas the growth rate of the CO_2 emission structure coefficient has rarely been studied. The CO_2 emission structure coefficient is a combination of the energy structure and CO_2 emission coefficients.

To facilitate analysis, we assumed that the CO_2 emission coefficients from the same source are constant and that there are only two types of energy sources: fossil energy (coal, oil and natural gas), which emits the most CO_2 during the input-output process, and nonfossil energy (wind, nuclear, etc.). As only fossil and nonfossil energy are considered, the change in the proportion of fossil energy in the total energy input is equal to the change in the proportion of nonfossil energy in the total energy input, albeit in an opposite direction, which means that $d\omega_1/dt = -d\omega_2/dt$. Thus, the growth rate of the CO_2 emission structural coefficient can be expressed as:

$$g_M = \frac{dM(t)/M(t)}{dt} = \frac{1}{w_1\eta_1 + w_2\eta_2}\left(\eta_1\frac{dw_1}{dt} + \eta_2\frac{dw_2}{dt}\right) = -\frac{1-\eta_2/\eta_1}{w_1 + w_2(\eta_2/\eta_1)} \times \frac{dw_2}{dt} \tag{10}$$

where η_1 and η_2 are the CO_2 emission coefficients of fossil energy and nonfossil energy, respectively. In general, the carbon coefficient of fossil energy is much larger than that of nonfossil energy, so it is reasonable to consider in rough calculations that $\eta_2/\eta_1 = 0$; then equation (10) can be expressed as:

$$g_M = -\frac{1}{w_1} \times \frac{dw_2}{dt} = -\frac{w_2}{w_1} \times g_{w_2} \tag{11}$$

Substituting equation (11) into equation (9), the growth rate of CO_2 emissions per capita in a balanced growth path ($g^{bgp}_{C/L}$) can be written as equation (12) or (13):

$$g^{bgp}_{C/L}(t) = \frac{1-\alpha}{\beta} \times g^{bgp}_{Y/L}(t) - \frac{w_2}{w_1} \times g_{w_2} - \frac{g}{\beta} \tag{12}$$

$$g^{bgp}_{Y/L}(t) = \frac{\beta}{1-\alpha} \times g^{bgp}_{C/L}(t) + \frac{\beta}{1-\alpha}\frac{w_2}{w_1} \times g_{w_2} + \frac{g}{1-\alpha} \tag{13}$$

The CO_2 emission intensity (CI: the amount of CO_2 emissions caused per unit of GDP growth) reflects the low carbon level in the economic system, which is $CI = C/Y$.

Let $VI = dCI/CI \times dt$, which is the rate of change in CO_2 emission intensity. If $VI > 0$, the intensity of CO_2 has increased (the low carbon level has fallen). If $VI < 0$, the intensity of CO_2 has decreased (the low carbon level has increased). If $VI = 0$, the intensity of CO_2 is unchanged (the low carbon level is unchanged).

According to the definition of the rate of change of CO_2 emission intensity, equation (14) can be obtained:

$$\begin{aligned} VI^{bgp} &= \frac{dCI^{bgp}}{CI^{bgp} \times dt} = g^{bgp}_{CI} = g^{bgp}_{C/L} - g^{bgp}_{Y/L} \\ &= \frac{1-\alpha-\beta}{1-\alpha} \times g^{bgp}_{C/L}(t) - \frac{\beta}{1-\alpha}\frac{w_2}{w_1} \times g_{w_2} - \frac{g}{1-\alpha} \end{aligned} \tag{14}$$

which intuitively describes the relationship between CO_2 emission intensity and per capita emission growth rate, as well as the CO_2 emission structural coefficient and the technology growth rate. A comprehensive analysis can be performed using this equation when a country or region (such as China) uses CO_2 emission intensity indicators to describe its environmental variables or CO_2 emission reduction targets.

3.4 Data acquisition and processing

The GDP was selected as the output of the production function and calculated at China's constant 2018 price. The total energy consumption was selected as the energy input, including fossil energy input and nonfossil energy input. The proportion of nonfossil energy in the energy input is expressed by the ratio of nonfossil energy to total energy consumption. The number of employed people (10,000 people) was selected as the labor input. The socioeconomic data for GDP, energy consumption and population were all taken from the China Statistical Yearbook.

As there is no direct access to capital stock, we estimated this factor based on the perpetual inventory method (PIM), which was proposed by Goldsmith (1951) and later extensively used by many authors. The PIM uses the principle of geometric decline to represent capital stock, which is expressed as follows:

$$K_t = K_{t-1} \times (1-\delta_t) + I_t/p_t \tag{15}$$

where K_t is the capital stock in year t; δ is the capital depreciation rate, which is set generally as 9.6%; I_t is the investment in year t, and the total fixed capital formation is selected as the investment in year t; and p_t is the fixed asset investment price index in year t.

As the China Statistical Yearbooks only provide fixed asset investment price indexes since 1990, we fit the fixed assets investment price indexes before 1990 based on the relationships between the fixed asset investment price indexes after 1990 and the commodity retail price indexes. To avoid the continuity of the estimated capital stock from being affected by the starting year, in the process of estimating the capital stock, the base year was selected as far from the starting year of the time series data as possible considering the availability of data. In this study, the time range of the time series data selected for the estimated model parameters was 1978–2018 and 1974 was selected as the base year for estimating the capital stock. Based on the method previously provided (Jun *et al.*, 2004), the estimated value of capital stock in 1974 is as follows:

$$K_{1974} = \frac{I_{1974}}{d} \tag{16}$$

where d is the geometric average growth rate of investments from 1974 to 1977.

Covert $Y = AK^{\alpha}E^{\beta}L^{1-\alpha-\beta}$ into $Y/L = (K/L)^{\alpha}(E/L)^{\beta}A$ and take the logarithm of both sides and the derivative with respect to time t:

$$g_{Y/L}(t) = \alpha g_{K/L}(t) + \beta g_{E/L}(t) + g \tag{17}$$

After selecting the time-series data from 1978 to 2018 and using the ordinary least squares method to estimate the parameters in equation (17), we used the Dubin two-step method to modify the autocorrelation between variables. Then, the results of the parameters were obtained as follows:

$$\begin{aligned} g_{Y/L}(t) = {} & \underset{(0.00)}{0.414 g_{K/L}(t)} + \underset{(0.00)}{0.528 g_{E/L}(t)} + \underset{(0.32)}{0.039} \\ R^2 = {} & 0.87, DW = 1.81 \end{aligned} \tag{18}$$

where the values in parentheses are the significant values of the corresponding parameters.

As the return to scale of the production function was assumed to be constant, we calculated that the labor elasticity is $1 - \alpha - \beta = 0.058$, and the growth rate of the TFP (g) was 3.9%.

According to the China Statistical Yearbook, we estimated that the average annual growth rate of China's GDP from 1978 to 2018 was 9.42%, the growth rate of labor (n) was 1.66%, and the growth rate of population was 0.933%. Based on these results, the growth rate per capita GDP was 8.487%, the growth rate per capita CO_2 emissions was 4.08%, and the growth rate of the CO_2 emission structure coefficient (M) was −0.29%.

4. Results and discussion

4.1 Parameter estimation for Models 1–5

Based on the data retrieved from China Statistical Yearbook and the data estimated by equation (1), using the least squares method, the results of Models 1–5 are shown in Table 1.

The parameters of Model 1 show that per capita GDP has a positive impact on per capita CO_2 emissions; this impact is significant. The linear relationship hypothesis between the two variables remains valid, but the goodness of fit is low, so it was necessary to explore the influence of other factors.

The parameters of Model 2 show that the per capita GDP and the proportion of nonfossil energy consumption, respectively, have positive and negative impacts on per capita CO_2

emissions, and the linear relationship hypothesis between per capita CO_2 emissions, per capita GDP and the proportion of nonfossil energy consumption remains valid. The goodness of fit of Model 2 is greater than that of Model 1, and the proportion of nonfossil energy in the selected control variables is reasonable. Both Models 1 and 2 assume that the relationships between per capita CO_2 emissions and per capita GDP are linear and that the goodness of fit is low.

The parameters of Model 3 show that per capita GDP first has a positive effect on per capita CO_2 emission, followed by a negative effect. Per capita GDP and the quadratic power of GDP per capita have a significant impact on per capita CO_2 emissions, indicating that the hypothesis of the quadratic curve relationship between the two variables remains valid and that the goodness of fit is markedly improved compared to that of Model 1. According to Model 3, the quadratic coefficient of GDP per capita is negative, so China's EKC exists. This is consistent with a classical EKC, indicating the existence of the maximum value of CO_2 emissions per capita.

The parameters of Model 4 indicate that per capita GDP first has a positive impact on per capita CO_2 emissions, followed by a negative impact. The proportion of nonfossil energy consumption has a negative impact on per capita CO_2 emissions. Per capita GDP, the quadratic term of GDP per capita, the proportion of nonfossil energy consumption all have significant effects on per capita CO_2 emissions. The goodness of fit in Model 4 is greater than in Model 3. The proportion of nonfossil energy consumption is still reasonable.

The parameters of Model 5 indicate that GDP per capita first has a positive impact on per capita CO_2 emissions, followed by a negative impact. Both the proportion of nonfossil energy consumption and TFP have negative impacts on per capita CO_2 emissions. The effects of per capita GDP, the quadratic term of GDP per capita, the proportion of nonfossil energy consumption and the TFP are significant, with a goodness of fit of 94% and a reasonable selection of TFP.

To summarize, from the perspective of the causal relationship and statistical index analysis, the Chinese EKC described by Model 3 exists, but it is more reasonable to choose Model 5 to illustrate China's per capita CO_2 emissions. In addition to China's per capita GDP, which has a consistent relationship with the classical EKC, the EKC is affected by the proportion of nonfossil energy consumption and the TFP. Therefore, further studying the effects of per capita GDP, the proportion of nonfossil energy consumption and the TFP on per capita CO_2 emissions is necessary.

4.2 Conditions for changes in per capita CO_2 emissions

To stop the growth of CO_2 emissions per capita, $g_{C/L}^{bgp}(t) \leq 0$ should be met. According to equation (12):

Parameters	Model 1	Model 2	Model 3	Model 4	Model 5
β_0	0.932 (0.01)	1.052 (0.05)	−0.278 (0.42)	0.438 (0.01)	1.106 (0.00)
β_1	0.266 (0.00)	0.327 (0.00)	0.849 (0.01)	0.721 (0.00)	0.991 (0.00)
β_2		−0.055 (0.00)	−0.044 (0.00)	−0.033 (0.00)	−0.054 (0.00)
β_3				−0.052 (0.00)	−0.040 (0.00)
β_4					−1.791 (0.00)
	$R^2 = 0.46$	$R^2 = 0.60$	$R^2 = 0.68$	$R^2 = 0.89$	$R^2 = 0.94$
	$DW = 1.59$	$DW = 1.61$	$DW = 1.95$	$DW = 1.82$	$DW = 1.87$

Table 1.
Parameters' estimation value for Models 1–5

$$g_{Y/L}^{bgp}(t) \leq \frac{\beta}{1-\alpha}\left(\frac{w_2}{w_1} \times g_{w_2} + \frac{g}{\beta}\right) \quad (19)$$

The term $(\beta/(1-\alpha))(w_2/w_1 \cdot g_{w_2} + g/\beta)$ can be considered the sum of the efficiency and structural growth rate. According to equations (12) and (19), the growth rate of per capita CO_2 emissions is positively correlated with the growth rate of per capita output and negatively correlated with the growth rate of the proportion of nonfossil energy and the growth rate of knowledge. This helps to explain the parameter symbols in Model 5. Existing environmental EKCs reveal a parabolic relationship between per capita CO_2 emissions and output per capita, but they do not reveal the reason for this relationship. The reason for this relationship is mainly that the sign for the growth rate of per capita CO_2 emissions depends on the difference between the growth rate of per capita output and the sum of the efficiency and structural growth rate, not only the growth rate of per capita output. The growth of per capita CO_2 emissions ceases when the growth rate of the output per capita is less than or equal to the sum of efficiency and structural growth. This finding shows that technological progress and the optimization of energy structures are important factors in reducing per capita CO_2 emissions. Per capita CO_2 emissions do not automatically show a trend of increasing first and then decreasing as per capita output increases. The key in this relationship lies in whether the sum of the efficiency and the structural growth rate that reverses the growth of per capita CO_2 emissions are large enough to exceed the rate of per capita output.

The growth rate of per capita output, the sum of the efficiency and structural growth rate, and the growth rate of per capita CO_2 emissions in China from 1978 to 2018 are shown in Figures 1 and 2.

Figures 1 and 2 show that the growth rate of per capita output in most years of 1979–2018 was greater than the sum of efficiency and structural growth, and the growth rate of per capita

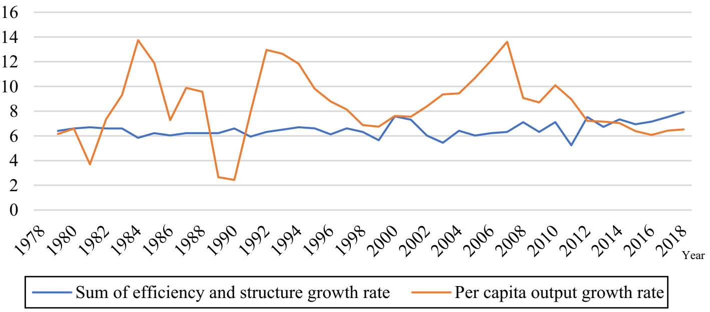

Figure 1. The growth rate of per capita output, the sum of efficiency and structure growth rate

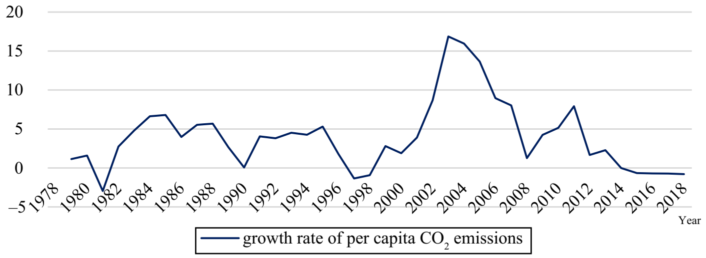

Figure 2. The growth rate of per capita CO_2 emissions

carbon dioxide emissions was greater than zero. Among the various years, the growth rate of per capita output in 1979–1981, 1989–1990 and 2014–2018 were less than the sum of efficiency and structural growth. The growth rate of per capita carbon dioxide emissions in these three stages do not correspond to the difference between the growth rate of per capita output and the sum of efficiency and structural growth rate, but they basically maintain the same trend. During 1979–1981, the growth rate of per capita CO_2 emissions in 1981 was less than zero. During 1989–1990, the growth rate of per capita CO_2 emissions in 1990 was close to zero. During 2014–2018, the growth rates of per capita CO_2 emissions were all less than zero. In 1997–1998, the growth rate of per capita CO_2 emissions was less than zero, while the growth rate of per capita output was greater than the sum of efficiency and the structural growth rate.

The proposal of the new normal concept in 2014 indicates that China's economy has entered a new stage distinct from its past period of rapid growth. A series of policies and measures have promoted structural adjustment and stable growth. The country's growth rate of per capita output has declined significantly, its innovation has improved meaningfully, and its energy structure has been optimized continuously. These changes of shifting from one to another will cause the growth rate of China's per capita output to be less than the sum of its efficiency and structural growth rate, and the growth rate of per capita CO_2 emissions for 2014–2018 was less than zero. This stage was the starting point for the decline in CO_2 emissions per capita in China, which may continue in the future, but the overall trend has been determined. This method of predicting the decline of CO_2 emissions per capita is more convincing than the turning point predicted by the traditional EKC and has potential flexibility for policymaking.

4.3 Growth rate range of China's per capita CO_2 emissions during the 13th five-year plan

According to the National Rules on Climate Change (2014–2020), China will ensure that its carbon emission intensity in 2020 is reduced by 40%–45% compared with 2005. If calculated according to the minimum target of 40%, the carbon emission intensity will not change by more than −3.351% annually. If calculated according to the maximum target of 45%, the carbon emission intensity will not change by more than −3.981% annually. According to equation (14), the actual decreases in China's carbon emission intensity in 2016–2018 were 6.42%, 6.39% and 6.28%, respectively. The decrease in China's CO_2 emission intensity since 2014 has been far beyond the planned target.

If China's carbon emission intensity is roughly reduced by 7% per year in the future, if the economic growth rate is 6.5% (the expected target of the 13th Five Year Plan of China), and if the population growth rate is 0.933%, then $g^{bgp}_{Y/L}(t) \geq g^{*}_{Y/L} = 5.567\%$, $VI^{bgp} \leq VI^{*} = -7\%$. By transforming equations (12) and (14), we obtain:

$$\frac{1-\alpha}{\beta} \times g^{*}_{Y/L} - \frac{w_2}{w_1} \times g_{w_2} - \frac{g}{\beta} \leq g^{bgp}_{C/L} \leq \frac{1-\alpha}{1-\alpha-\beta}\left[VI^{*} + \frac{\beta}{1-\alpha}\frac{w_2}{w_1} \times g_{w_2} + \frac{g}{1-\alpha}\right] \quad (20)$$

Assuming that the growth rate of technological progress during the 13th Five-Year Plan period is 3.9%, and the elasticity of capital, energy and labor remains unchanged, we calculated that the change range of China's per capita CO_2 emissions during the 13th Five-Year Plan period will be [−0.92%, 6.1%]. The economic growth target would be achieved for a geometric average value that is greater than or equal to the lower limit of the range of per capita CO_2 fluctuations, and the CO_2 intensity reduction target would be guaranteed for a geometric average value that is less than or equal to the upper limit.

The growth rates of per capita CO_2 emissions for the three consecutive years from 2016 to 2018 were −0.707%, −0.713% and −0.798%, respectively, indicating that China is likely to achieve its goal of economic growth and its goal to reduce its CO_2 emission intensity during the 13th Five-Year Plan period.

5. Policy recommendations

Clearly, CO_2 emissions are a global problem, and ultimately climate change will change everyone – through heat, drought, fire and its impact on the economy and health. This is inescapable and every country must take responsibility. China, one of the largest economies, should set an example. Controlling carbon emissions requires scientific measurement and evaluation, and better links with people's daily life. This is the important significance of this study to discuss growth and carbon emissions from the perspective of per capita.

5.1 Continue to maintain balanced growth

Our findings show that the decrease in the growth rate of per capita output and the increase in the sum of efficiency and structural growth in 2014–2018 reversed the trend of the continuous growth of per capita CO_2 emissions. China has made great strides in air pollution control. The air pollution reduction in China in seven years is almost equal to that in the USA in 30 years. Compared with the conclusions of the existing literature, the findings in this work are different in the existence and form of the EKC due to the different research objects, environmental variables and sample data. According to the conclusions of this paper, we propose different policy recommendations. The appropriate economic growth rate target must still be chosen for a balanced growth path to achieve the sustainable development based on a balance of economic structures. At present, China's economy has entered a new stage called the new normal. The goals of structural adjustment must not be changed in pursuit of high-speed growth that deviates from the balanced growth path. To seize a favorable opportunity for global economic recovery, China should continue to exert pressure on energy-intensive industries to accelerate the formation of sustainable economic development, as well as take advantage of the current momentum of innovation in science, technology and consumption to cultivate new areas of economic growth with high levels of new technology and sustainable development.

5.2 Persistently optimizing the energy structure 0 and develop new energy sources

China accounts for 43% of the global renewable energy investment and is the largest producer of photovoltaic cells and modules. According to the data of the International Monetary Fund, between 2016 and 2021, the average annual economic growth rate of China was 6.1%, while the average annual growth rate of energy consumption was only 2.8%, accounting for about half of the world's energy savings in the same period. Nearly 16% of China's total energy comes from nonfossil energy. The results also show that in the future China will maintain a medium-high speed of growth, and its per capita output growth rate will also remain at a medium-high rate. To reduce the growth rate of per capita CO_2 emissions, the sum of efficiency and structural growth rate must be maintained at a high level. Optimizing the energy structures (i.e. reducing the proportion of fossil energy in the energy input and increasing the proportion of nonfossil energy) can reduce the growth rate of the CO_2 structural coefficient and increase the sum of efficiency and structural growth. The proportion of nonfossil energy in China's energy structure has recently steadily increased, but the proportion of nonfossil energy has remained low compared to that of fossil energy, and its growth rate has been slower. The space to optimize this energy structure is large, and this task remains arduous and urgent.

5.3 Improving the total factor productivity growth rate

The sum of efficiency and structural growth is affected not only by the optimization of the energy structure but also by the growth rate of knowledge (the growth rate of TFP). Based on the data of total fixed capital formation and capital stock from 1978 to 2018, China's total fixed capital formation and capital stock grew at a higher rate after the US subprime mortgage crisis in 2008, and the growth rate of the total factor productivity shows a downward trend. The elements (capital, labor and energy) in economic growth contribute a large share, while technological progress contributes a small share, and the level of technological progress is low. Therefore, to prevent the per capita CO_2 emissions from increasing for a long time, in addition to optimizing the energy structure, China should improve the growth rate of TFP and increase the growth rate of its total factor productivity, which can ensure the growth rate of per capita output is lower than the sum of efficiency and structural growth rate for a long time.

To sum up, this work argues that the situation of EKC needs to be analyzed separately in combination with a region, time period and economic development stage. Every country, region and stage of development needs careful and scientific analysis to make decisions that are in line with the actual situation. Therefore, the future research should be enriched and expanded in the sample area, time, development stage, etc.

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