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RESEARCH ARTICLE

Decoupling relationship between carbon emissions and economic development and prediction of carbon emissions in Henan Province: based on Tapio method and STIRPAT model

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Abstract
In order to cope with global warming, China has put forward the "30 · 60" plan. We take Henan Province as an example to explore the accessibility of the plan. Tapio decoupling model is used to discuss the relationship between carbon emissions and economy in Henan Province. The influence factors of carbon emissions in Henan Province were studied by using STIRPAT extended model and ridge regression method, and the carbon emission prediction equation was obtained. On this basis, the standard development scenario, low-carbon development scenario, and high-speed development scenario are set according to the economic development model to analyze and predict the carbon emissions of Henan Province from 2020 to 2040. The results show that energy intensity effect and energy structure effect can promote the optimization of the relationship between economy and carbon emissions in Henan Province. Energy structure and carbon emission intensity have a significant negative impact on carbon emissions, while industrial structure has a significant positive impact on carbon emissions. Henan Province can achieve the "carbon peak" goal by 2030 years under the standard and low-carbon development scenario, but it cannot achieve this goal under the high-speed development scenario. Therefore, in order to achieve the goals of "carbon peaking" and "carbon neutralization" as scheduled, Henan Province must adjust its industrial structure, optimize its energy consumption structure, improve energy efficiency, and reduce energy intensity.

Keywords Tapio decoupling model · STIRPAT model · Ridge regression · Carbon emission forecast · Scenario analysis · Henan Province

Introduction

In recent years, abnormal climate change has brought great challenges to human daily life and economic development (Espoir and Sunge 2021). For example, Velicogna I et al. (2006) found that the melting of the Greenland ice sheet caused an annual rise in sea level of $0.5 \pm 0.1 \mathrm{mmyear}^{-1}$ between 2002 and 2006, which posed a huge threat to the production of residents in coastal cities and islands. Tom K et al. (2018) found that global warming would make the world economy face a potential loss of $9.59371 trillion. O'Neal E T (2014) believed that climate change would cause political instability in developing countries and lead to rising food prices, riots, revolutions, and other situations. Fox D M et al. (2018) believed that global warming would increase the burning area of forests. Malikov Emir et al. (2020) concluded that climate change will reduce crop yields and cause economic losses.

At the same time, the economic development of various countries has become increasingly difficult because of the continued prevalence of COVID-19 worldwide. Obviously, economy is not only the main cause of environmental problems, but also the essential basic condition for solving environmental problems. Only in a certain natural and social environment can economic development proceed rapidly.

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Due to the excessive use of natural resources and the uncontrolled emission of carbon dioxide and other greenhouse gases, the earth has been irreversibly damaged, which has prompted countries to gradually move towards the road of developing a "green economy". It has become a general consensus of the international community to achieve economic recovery through green low-carbon development (Nations U 2015; Nations U U 2015). More and more countries are engaged in the cause of "carbon peak" and "carbon neutrality" (Zhao 2022b).

China has been actively and forcefully addressing climate change and fulfilling the responsibilities of a major country. In addition, China promised to implement the "30 · 60" plan at the United Nations General Assembly, which is the national action plan for the green transformation of energy, and strive to achieve "carbon peak" by 2030 and "carbon neutral" by 2060. At the national two sessions in 2021, the Party Central Committee included "carbon peaking and carbon neutralization" in the government work report and clearly incorporated "carbon peaking and carbon neutralization" into the overall layout of ecological civilization construction (Wu et al. 2022).

As a major province of population, agriculture and industry in China, the energy consumption intensity of Henan Province in recent years is much higher than the national average level, and its carbon emissions are also gradually increasing with the economic development (Cai et al. 2022). Therefore, it is necessary to study the current situation of the relationship between carbon emissions and economy in Henan Province and the relationship between carbon emissions and various social factors (demographic factors, economic factors, etc.). After knowing the current situation of the relationship between carbon emissions and economy, and the relationship between carbon emissions and various social factors, Henan Province can have a deeper understanding of its own situation, and implement measures to control carbon emissions according to specific factors, so as to contribute to the realization of the "30 · 60" plan in China. This paper uses Tapio decoupling model to explore the relationship between carbon emissions and economy in Henan Province from 2000 to 2019 and then uses STIRPAT expansion model to study the influencing factors of carbon emissions in Henan Province and predict its carbon emissions from 2020 to 2040.

Data source and carbon emission calculation

Data source

The data used in this paper are from the statistical yearbook of Henan Province and the data of the National Bureau of statistics.

Carbon emission calculation formula

Since the Statistics Bureau of Henan Province has not published the carbon dioxide emission data, this paper obtains the following carbon emission measurement formulas related to this study by consulting the IPCC carbon emission calculation guidelines and China emission accounts and datasets and combining the national conditions (IPCC 2014):

The formula for converting energy to standard coal:

$$\mathrm{SC_i} = \mathrm{EC_i} \times \mathrm{CCS_i} \tag{1}$$

The total energy CO2 emission formula:

$$\mathrm{CE^e} = \sum_{i=1}^{9} \mathrm{EC_i} \times \mathrm{MLCV_i} \times \mathrm{CC_i} \times \mathrm{COR_i} \times \frac{44}{12} = \sum_{i=1}^{9} \mathrm{E_i} \times \mathrm{CDEC_i} \tag{2}$$

Similarly, the CO2 emission formula of single energy can be obtained:

$$\mathrm{CE_i^e} = \mathrm{EC_i} \times \mathrm{MLCV_i} \times \mathrm{CC_i} \times \mathrm{COR_i} \times \frac{14}{12} = \mathrm{EC_i} \times \mathrm{CDEC_i} \tag{3}$$

where EC_i is the energy consumption; CCS_i refers to the energy conversion coefficient of standard coal; SC_i refers to the amount of standard coal corresponding to energy; $MLCV_i$ is the average low calorific value of energy; CC_i is the carbon content per unit calorific value; COR_i is the carbon oxidation rate of energy; $CDEC_i$ refers to carbon dioxide emission coefficient; and i refers to energy type (Dong and Li 2022). The standard coal coefficient and carbon dioxide emission coefficient of different energy sources are shown in Table 1 (see the attached draft for the description of the table).

If there is a year with missing statistical data, or the statistical data is obviously abnormal compared with the previous and subsequent years, but there is no obvious basis, its carbon emissions will be corrected by the following methods:

$$\mathrm{CE_{t1,i}} = \mathrm{CE_{t0,i}} \times (1 + \mathrm{agr})^{\mathrm{t1-t0}} \tag{4}$$

where $CE_{t1,i}$ is the carbon emission of the ith energy in the correction year; $CE_{t0,i}$ is the carbon emission of the ith energy in the reference year; and agr is the average annual growth rate of carbon emission. Correction means that assuming that the growth rate of carbon emission remains unchanged, the carbon emission in the correction year is calculated based on the emission in the reference year (Guan et al. 2021).

Carbon emission intensity refers to the carbon emissions per unit of GDP growth. This indicator is mainly used to measure the relationship between economy and carbon emission. The calculation formula of carbon emission intensity is as follows:

Table 1 Standard coal and carbon dioxide emission coefficient

Energy	Average low calorific value (kJ/kg)	Conversion coefficient of standard coal (kgce/kg)	Carbon content per unit calorific value (ton carbon/TJ)	Carbon oxidation rate	CO^2 emission coefficient (kg-CO^2/kg)
Raw coal	20,908	0.7143	26.37	0.94	1.9003
Coke	28,435	0.9714	29.5	0.93	2.8604
Crude oil	41,816	1.4286	20.1	0.98	3.0202
Fuel oil	41,816	1.4286	21.1	0.98	3.1705
Gasoline	43,070	1.4714	18.9	0.98	2.9251
Kerosene	43,070	1.4714	19.5	0.98	3.0179
Diesel oil	42,652	1.4571	20.2	0.98	3.0959
Oil field natural gas	38,931	1.3300	15.3	0.99	2.1622
Power		1.229 (10,000 kwh/ton)			1.246 kg/kW.h

$$\text{Carbon emission intensity} = \frac{\text{Carbon emissions}}{\text{GDP}} \quad (5)$$

To sum up, the energy data of Henan Province are calculated and processed by using the above formula in combination with Table 1, and the consumption, carbon dioxide emissions, and total carbon emissions of various energy sources converted into standard coal in Henan Province from 2000 to 2019 can be obtained.

Literature review

The decoupling relationship between carbon emissions and economy

At present, the development of the world economy will inevitably lead to the emission of carbon dioxide, and the study of the relationship between the two has been attracting the attention of scholars at home and abroad. At present, the main methods to study the relationship between economy and carbon emissions are the carbon emission environment Kuznets curve (EKC) model, which focuses on the long-term development trend of carbon emissions and economy, and the decoupling model, which focuses on the short-term changes of the two. EKC was put forward by Grossman and Krueger in 1995, and studies such as Tan et al. (2015) and Usama Al-mulali et al. (2015) support this view. However, some scholars still questioned it (Io and Aa 2010; Vo et al. 2019), and Munir Q et al. (2020) proved that the causal relationship between EKC curve and CO_2, EC, and GDP is misleading. Because the EKC curve is misleading, decoupling analysis is now considered to be the best method to study the relationship between carbon emissions and the economy (Dong et al. 2016).

Decoupling analysis originated from the OECD's report "Indicators for Measuring the Decoupling Relationship between Economic Growth and Environmental Impact" released in 2002 to study the relationship between environmental pollution and economy. Later, Petri Tapio (2005) built the "Tapio decoupling model" by introducing the elastic method, and subdivided the decoupling state into eight states, such as strong decoupling and weak decoupling.

However, the above article only uses the decoupling theory to analyze the decoupling relationship between carbon emissions and economy, and cannot show the reasons for the change of decoupling status. At present, the main methods to study the factors affecting carbon emissions are structural decompression analysis (SDA) and index decompression analysis (IAD). The data used for the two methods are the input–output table and part of the total data. Therefore, IAD has lower data requirements, simpler operation, and wider application range. IAD is mainly divided into logarithmic mean Laspeyres index (LMLI) and logarithmic mean division index (LMDI) (Zhang and Wang 2021). Among them, LMDI can solve the problem of zero value and residual in the decomposition process, so many scholars will use LMDI to deeply study the factors affecting the decoupling state when studying the decoupling relationship between economy and carbon emissions (Ang et al. 2015).

Based on the Tapio decoupling model and LMDI decomposition method, Wang Z and Yang L (2015) explored the decoupling relationship between industrial growth and environmental pressure in the Beijing-Tianjin-Hebei (BTH) economic belt from 1996 to 2010. The study showed that energy structure and energy intensity made a great contribution to industrial decoupling, and there was no obvious trend in industrial structure. Zhao Xiaochun et al. (2022a) studied the relationship between China's carbon emissions and economic development from 2009 to 2019. The study showed that population size and economic intensity can inhibit the decoupling of carbon emissions, while energy intensity and carbon intensity have a positive effect.

Carbon emission peak prediction

At present, the main carbon emission prediction methods can be roughly divided into three categories: (1) Describe the carbon emission trend through EKC model, and predict the peak value of carbon emissions according to whether there is an inflection point. (2) After determining the influencing factors of carbon emissions, the future development of carbon emissions is predicted and analyzed in combination with the scenario analysis method. The models for decomposing the influencing factors of carbon emissions mainly include LMDI, IPAT, and Stochastic Impacts by Region on Population, Affluence, and Technology (STIRPAT). (3) The carbon emissions are directly predicted and analyzed through system modeling methods, including computable general equilibrium (GGE) and gray system prediction method.

Liu H et al. (2018) explored the relationship between the environmental conditions and economic development of Japan, South Korea, and China through the EKC curve and studied the development trend of their economic development and ecological footprint. Awaworyi C S et al.'s (2018) study found that there are many relationships between economy and carbon emissions. Zhong Mao-chu et al. (2010) found that the EKC curve theory has serious defects, such as random selection of indicators and weak interpretation of the model. Therefore, the application should carefully consider and use this method to predict carbon emissions.

Ehrlich and Holdren proposed the IPAT model in the 1970s to study the impact of population, economy, and technology on environmental pressure. However, it assumes that the influence factors and environmental pressure are proportional changes, so it is more troublesome to use. Later, Dietz et al. (1997) revised it and proposed the STIRPAT model. Zhang C et al. (2019) based on the scenario analysis method and STIRPAT model, discussed the trend of China's future carbon emissions from the perspective of the industry. The study showed that China may achieve the carbon peak in 2030, and the key task of future carbon emissions reduction is to implement more strict industrial and energy structure transformation policies. Cui L et al. (2019) explored the relationship between China's carbon emissions and energy consumption by building a CGE model. Li F et al. (2018) used the improved IPAT model to calculate China's carbon emission intensity and then further used the gray correlation model to predict carbon emissions in 2030. The study found that if China's total GDP is less than 151,426.15 billion yuan in 2030, it is possible to achieve the carbon peak.

From the perspective of research methods, STIRPAT model combined with scenario analysis method is the current mainstream carbon emission prediction method, which can combine policy requirements to explore the change trend of carbon emissions in different scenarios and help researchers judge which scenario is the most appropriate.

Decoupling relationship analysis

This paper uses the Tapio decoupling model to judge the relationship between carbon emissions and economic development in Henan Province from 2000 to 2019, and then combines Kaya identity and LMDI decomposition to explore the root causes of the relationship between them, so as to better understand the deep-seated reasons for the transformation of the relationship between carbon emissions and economic development in Henan Province.

Introduction to Tapio model

"Decoupling" means that in economic development, the total energy consumption of materials increases with the growth of the total economic volume at the initial stage of industrial development. However, when the economy and technology develop to a certain level, the total energy consumption of materials shows a downward trend, but the economy still shows a growth trend (Rajabi Kouyakhi 2022).

Because Tapio decoupling model has the following characteristics: (1) It focuses on the changes of individuals in different years. (2) It has 8 decoupling states: strong decoupling, weak decoupling, declining decoupling, extended connection, declining connection, weak negative decoupling, expanded negative decoupling, and strong negative decoupling (Zhang et al. 2022a). At the same time, we combine the advantages, disadvantages, and characteristics of the corresponding methods introduced in the literature review. We decided to explore the relationship between economic development and carbon emissions in Henan Province by combining it with LMDI.

Tapio model definition

The model equation is set as formula (6):

$$\varepsilon = \frac{\Delta C\%}{\Delta Y\%} = \frac{\frac{C_t - C_0}{C_0}}{\frac{Y_t - Y_0}{Y_0}} \tag{6}$$

where ε refers to the decoupling index between carbon emissions and GDP from year 0 of the start (study start) to year t of the end (study end); C_t and C_0 refer to the carbon emissions in the start year and the end year, respectively, i.e., environmental pressure; Y_0 means GDP in the starting year; Y_t is the GDP of the end year; and ΔC% and ΔY% represent the increase rates of carbon emissions and GDP in the beginning and end years, respectively (Xu et al. 2021) (Table 2).

Table 2 Classification criteria for decoupling status of Tapio decoupling model

Decoupling status		ΔC%	ΔY%	ε	Significance
Decoupling	Strong decoupling	$(-\infty, 0)$	$(0, +\infty)$	$(-\infty, 0)$	Reduce carbon emissions and increase GDP
	Weak decoupling	$(0, +\infty)$	$(0, +\infty)$	$[0, 0.8)$	GDP growth is greater than carbon emission growth
	Recessive decoupling	$(-\infty, 0)$	$(-\infty, 0)$	$[1.2, +\infty)$	The reduction rate of carbon emissions is greater than that of GDP
Connect	Expansion connection	$(0, +\infty)$	$(0, +\infty)$	$[0.8, 1.2)$	Carbon emissions and GDP growth are similar
	Decay connection	$(-\infty, 0)$	$(-\infty, 0)$	$[0.8, 1.2)$	Carbon emissions and GDP decrease at a similar rate
Negative decoupling	Weak negative decoupling	$(-\infty, 0)$	$(-\infty, 0)$	$[0, 0.8)$	The reduction rate of carbon emissions is less than that of GDP
	Expansion negative decoupling	$(0, +\infty)$	$(0, +\infty)$	$[1.2, +\infty)$	The growth rate of carbon emissions is greater than that of GDP
	Strong negative decoupling	$(0, +\infty)$	$(-\infty, 0)$	$(-\infty, 0)$	Carbon emissions increased and GDP decreased

Tapio model construction

This paper combines Kaya identity, LMDI decomposition, and Tapio decoupling model to build a decoupling model for carbon emission intensity effect, energy structure effect, energy intensity effect, economic level effect, and population effect of carbon emissions (Guo et al. 2021). The decoupling model is constructed as follows:

$$C = \sum_i^n C_i = \sum_i^n \frac{C_i}{E_i} \times \frac{E_i}{E} \times \frac{E}{GDP} \times \frac{GDP}{POP} \times P = \sum_i^n CI_i \times ES_i \times EI \times G \times P \tag{7}$$

where C represents carbon emissions; C_i refers to the carbon emission of the ith energy; E_i refers to the consumption of the ith energy (which has been converted into standard coal in this paper; E, GDP, and P refer to the total energy consumption, GDP, and permanent population, respectively; CI_i refers to the carbon emission intensity effect of the ith energy; ES_i refers to the energy structure effect of the ith energy; EI means energy intensity effect; G refers to economic level effect; and P is the population effect (Liu et al. 2022).

It is assumed that the total carbon emissions in the start year and the end year are C_0 and C_t. At this time, the change of total carbon emissions within 2 years can be set as ΔC. According to formula (7), ΔC can be decomposed into ΔC_{CI}, ΔC_{ES}, ΔC_{EI}, ΔC_G, and ΔC_P. Therefore, the formula can be converted into:

$$\Delta C = C_t - C_0 = \sum_i^n CI_{it} \times ES_{it} \times EI_t \times G_t \times P_t - \sum_i^n CI_{i0} \times ES_{i0} \times EI_0 \times G_0 \times P_0$$

$$= \Delta C_{CI} + \Delta C_{ES} + \Delta C_{EI} + \Delta C_G + \Delta C_P \tag{8}$$

where ΔC factors are calculated in a similar way. Due to space reasons, this article only shows ΔC_{CI} calculation method:

$$\Delta C_{CI} = \sum_i^n L(C_{it} C_{i0}) \ln\left(\frac{Cl_{it}}{Cl_{i0}}\right) \tag{9}$$

$$L(C_{it}, C_{i0}) \begin{cases} C_{it}, C_{it} = C_{i0} \\ \frac{C_{it} - C_{i0}}{\ln C_{it} - \ln C_{i0}}, C_{it} \neq C_{i0} \end{cases} \tag{10}$$

The other formulas are only different in $\ln(\frac{Cl_{it}}{Cl_{i0}})$.

In conclusion, the decoupling elasticity between carbon emissions and GDP growth can be decomposed again (Xiong et al. 2022), as follows:

$$\varepsilon = \frac{\frac{\Delta C}{C^0}}{\frac{\Delta Y}{Y^0}} = (\Delta C_{CI} + \Delta C_{ES} + \Delta C_{EI} + \Delta C_G + \Delta C_P) \times \frac{\frac{1}{C^0}}{\frac{\Delta Y}{Y^0}} = \varepsilon_{CI} + \varepsilon_{ES} + \varepsilon_{EI} + \varepsilon_G + \varepsilon_p \tag{11}$$

where $CI_i = \frac{C_i}{E_i}$ is essentially the carbon dioxide emission coefficient of various energy sources, so this value does not change with time, so it is 0 after taking the logarithm. Therefore, the formula can be simplified to formula (12):

$$\varepsilon = \varepsilon_{ES} + \varepsilon_{EI} + \varepsilon_G + \varepsilon_p \tag{12}$$

Overall decoupling analysis

The decoupling status between economic growth and carbon emissions in Henan Province from 2000 to 2019 and the elastic coefficients of the four impact effects are obtained after calculating the indicators in combination with the decoupling model formula (see Table 3 for details).

ES_i refers to the energy structure effect of the ith energy; EI means energy intensity effect; G refers to economic level effect; and P stands for population effect.

Therefore, the following conclusions can be drawn from Table 3 and Fig. 1:

1) The score of economic level effect is positive, and the overall elasticity coefficient is 0.647, so the decoupling elasticity coefficient will increase with the increase of economic level effect coefficient, so the economic level

effect of Henan Province has a significant inhibitory effect on Tapio elasticity coefficient, which indicates that Henan Province should pay attention to high-quality economic development rather than blindly developing economy in order to achieve "carbon peak" and "carbon neutral".

2) The energy intensity effect is negative, and the overall elastic coefficient is − 0.239, so the energy intensity effect can promote the decoupling of Henan Province;
3) The elasticity coefficient of energy structure effect is − 0.003, so it also plays a role in promoting the overall elasticity coefficient of Henan Province, but the overall observation data shows that it has little change, which is related to the long-term energy structure in which fossil energy is the main energy in Henan Province. Therefore, Henan Province should pay attention to improving the energy structure and reasonably increase the proportion of new energy in the energy structure;
4) The elasticity coefficient of population effect is 0.012, so it can be considered that it has a restraining effect on the overall elasticity coefficient of Henan Province, which has a great relationship with the fact that Henan Province is a populous province. Therefore, Henan Province should publicize the concept of eugenics to the public and control the blind growth of population while cultivating high-quality talents.
5) The decoupling status of Henan Province was only "connected" and "negative decoupling" before 2005. From 2006 to 2019, the decoupling status of Henan Province remained between "weak decoupling" and "strong decoupling", which shows that in recent years, through the efforts of various channels, Henan Province has not only made achievements in economic development, but also made certain achievements in energy conservation, emission reduction, and environmental protection.
6) The fluctuation of energy intensity effect is basically synchronized with the elasticity coefficient, and the change of carbon emission intensity effect, economic level effect, and population effect is not large. Therefore, if Henan Province wants to maintain a strong decoupling state, energy consumption and GDP should show a downward and growth trend respectively, so as to maximize the energy intensity effect.

Table 3 Decoupling coefficient

Year	ε_{ES}	ε_{EI}	ε_{G}	ε_{p}	%ΔC	%ΔY	ε	Decoupling status
2000–2001	0.061	− 0.319	0.911	0.077	0.069	0.095	0.73	Expansion connection
2001–2002	0.11	− 0.032	0.933	0.070	0.098	0.091	1.081	Expansion connection
2002–2003	0.327	− 0.909	0.91	0.038	0.055	0.15	0.366	Weak decoupling
2003–2004	− 0.234	0.914	1.029	0.028	0.367	0.212	1.737	Expansion negative decoupling
2004–2005	0.009	− 0.055	1.173	− 0.178	0.207	0.218	0.949	Expansion connection
2005–2006	0.002	− 0.197	0.976	0.008	0.134	0.169	0.79	Weak decoupling
2006–2007	0.024	− 0.504	0.961	− 0.015	0.111	0.238	0.467	Weak decoupling
2007–2008	0.003	− 0.758	0.89	0.038	0.034	0.196	0.174	Weak decoupling
2008–2009	0.007	− 0.681	0.897	0.076	0.024	0.081	0.299	Weak decoupling
2009–2010	− 0.014	− 0.499	1.005	− 0.050	0.08	0.181	0.442	Weak decoupling
2010–2011	− 0.022	− 0.332	0.934	0.039	0.1	0.162	0.618	Weak decoupling
2011–2012	− 0.218	− 1.437	0.845	0.072	− 0.074	0.1	− 0.738	Strong decoupling
2012–2013	− 0.001	− 1.048	0.906	0.046	− 0.009	0.092	− 0.098	Weak decoupling
2013–2014	− 0.04	− 0.918	0.875	0.080	0	0.093	− 0.003	Strong decoupling
2014–2015	− 0.152	− 0.896	0.883	0.080	− 0.006	0.073	− 0.086	Strong decoupling
2015–2016	− 0.059	− 1.009	0.863	0.092	− 0.01	0.085	− 0.113	Weak decoupling
2016–2017	0.025	− 1.278	0.884	0.045	− 0.037	0.114	− 0.325	Strong decoupling
2017–2018	0.027	− 1.126	0.906	0.031	− 0.018	0.114	− 0.162	Weak decoupling
2018–2019	− 0.125	− 1.835	0.878	0.047	− 0.078	0.076	− 1.034	Strong decoupling
2000–2005	0.03	− 0.016	1.019	− 0.016	1.045	1.027	1.017	Weak decoupling
2005–2010	0.005	− 0.431	0.787	0.003	0.441	1.212	0.364	Weak decoupling
2010–2015	− 0.064	− 0.704	0.723	0.049	0.003	0.637	0.004	Weak decoupling
2015–2019	− 0.019	− 1.052	0.723	0.042	− 0.137	0.449	− 0.306	Strong decoupling
2000–2019	− 0.003	− 0.239	0.647	0.012	4.018	9.631	0.417	Weak decoupling

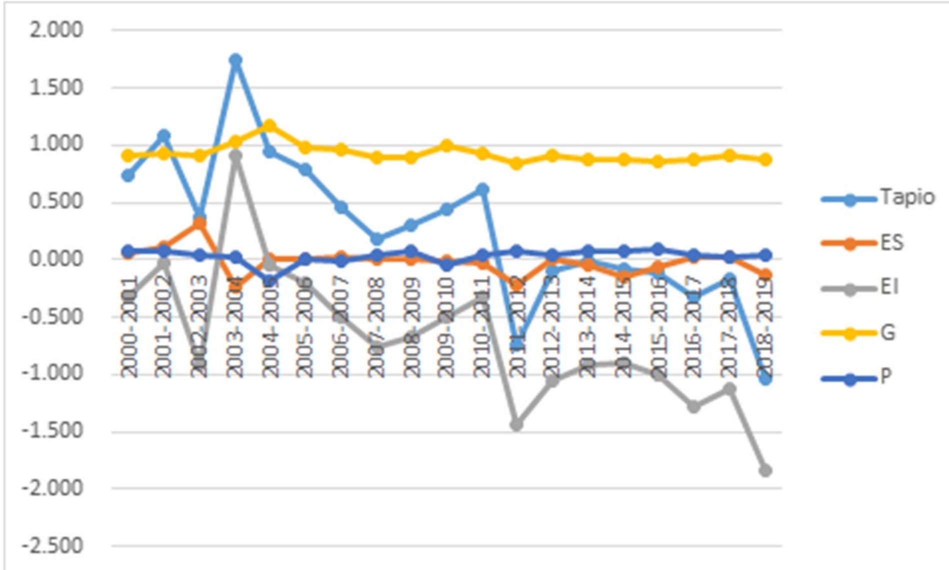

Fig. 1 Elasticity coefficient diagram

Carbon emission trend and peak prediction

After knowing the current situation of decoupling between carbon emissions and economic development in Henan Province, in order to understand the future development trend of carbon emissions in Henan Province, this paper uses STIRPAT model to predict three development scenarios in Henan Province from 2020 to 2040: high-speed development scenario, standard development scenario, and low-carbon carbon carbons emissions.

Introduction to STIRPAT model

STIRPAT model is an extension of the classical model IPAT model, which believes that environmental pressure is the result of the joint action of population size, economic development, and technological progress (Liu and Han 2021). At present, this model is widely used to study the influencing factors and trend prediction of environmental pollution (Ma et al. 2022). The basic form of the model is:

$$I = aP^bA^cT^de \tag{13}$$

where I represents environmental pressure; P represents demographic factors; A represents wealth factors; and T represents technical level. a is the model coefficient; b, c, and d are the elasticity coefficients of population, wealth, and technology, respectively; and e is the error term (Zhang et al. 2022b).

STIRPAT model definition

Based on the practices of Meng Ming (Meng and Zhou 2020) and Lin Xinru (Lin et al. 2020), combined with the development characteristics (Yuan et al. 2022), the STIRPAT model for carbon emission prediction in Henan Province is constructed by selecting passenger turnover (PT), total output value of agriculture, forestry, animal husbandry and fishery (TOV), energy structure (coal, ES), industrial structure (proportion of the secondary industry, IS), energy intensity (EI), carbon emission intensity (CEI), urbanization rate (UR), and per capita GDP (PCGDP). In order to facilitate calculation and data analysis, the model equation is transformed into a linear equation, and the model expansion formula is (Huang et al. 2022):

$$\begin{aligned} lnI_t = lna + blnPT_t + clnTOV_t + dlnES_t \\ + elnIS_t + flnEI_t + glnCEI_t \\ + hlnUR_t + ilnPCGDP_t + lne_t \end{aligned} \tag{14}$$

In this paper, the common least square method is used to estimate each variable to judge whether there is multicollinearity between I and PT, TOV, ES, IS, EI, CEI, UR, and PCGDP (see Table 4 for test results of collinearity of STIRPAT model).

It can be seen from Table 4 that the VIF values of all variables are greater than the maximum tolerance of 10, indicating that there is serious multicollinearity between explanatory variables, and the reliability of the regression coefficient of the common least square method is low, which cannot effectively explain the carbon emission factor.

In order to ensure the validity of the model estimation results, ridge regression is used for fitting. Based on the relevant data of Henan Province from 2000 to 2019, SPSS 25 is used for ridge regression modeling. Taking 0.02 as the unit length and the ridge regression coefficient K between 0 and 1, the equation, ridge trace, and R^2 corresponding to different ridge parameter K values are obtained. The smaller the ridge regression parameter K value, the less information the sample data loses, and the higher the model accuracy.

According to the change of ridge trace diagram, when $K=0.30$, the coefficient gradually tends to be stable. After adjustment, R^2 reaches 0.938. The equation fitting is good. By testing the variance of simulation, it can be seen that $F = 36.69$, $SigF = 0.000 < 0.01$, indicating that the equation has statistical significance. The final ridge regression equation of carbon emission in Henan Province is:

$$lnI_t = 6.962 + 0.196lnPT_t + 0.171lnTOV_t + 0.088lnES_t + 1.633lnIS_t - 0.011lnEI_t - 0.011lnCEI_t + 0.299lnUR_t + 0.104\text{lnPCGDP}_t \quad (15)$$

Table 4 Collinearity test

Variable	Non standardized coefficient	t value	Sig	VIF
Constant	1.138	3.694	0.003	
lnpt	0.005	0.151	0.882	51.841
lntov	0.109	1.748	0.106	284.850
lnes	0.382	4.274	0.001	11.825
lnis	0.073	0.620	0.547	21.283
lnei	0.882	23.835	0.000	83.799
lnur	0.468	3.522	0.004	353.684
lnpcgdp	0.722	10.948	0.000	748.498
lncei	2.069	4.920	0.000	22,479.103
R^2	1.00			
F value	6185.830			
Sig.F	0.000			

It can be seen from the coefficient table attached that the degree of impact of each indicator variable on carbon emissions in Henan Province is in descending order: industrial structure (0.307); total output value of agriculture, forestry, animal husbandry, and fishery (0.221); per capita GDP (0.207); urbanization rate (0.203); passenger turnover (0.199); energy structure (0.016); energy intensity (− 0.013); and carbon emission intensity (− 0.013), of which only energy structure and carbon emission intensity have a negative impact.

This paper brings the data into the model to calculate the predicted value, and compares it with the actual value to verify the prediction accuracy of the model, as shown in Fig. 2. It can be seen visually that the simulated value is very close to the historical actual value, indicating that the model fitting effect is very good, and the remaining analysis can be carried out.

STIRPAT parameter settings

The scenario analysis is set according to the development policies and historical data of Henan Province. See the attached draft for the setting basis. Here, we set three development scenarios considering the economic development stage, industrial structure, and energy consumption structure of Henan Province. According to the "30 60" plan and national development strategy, the time is divided into 2020–2025, 2026–2030, 2031–2035, and 2036–2040. The predicted value of each variable from 2020 to 2040 is obtained from the set parameters. After logarithmic processing, the predicted value is brought into the above fitting equation of carbon emissions in Henan Province based on STIRPAT model to obtain the predicted value of future carbon emissions in Henan Province.

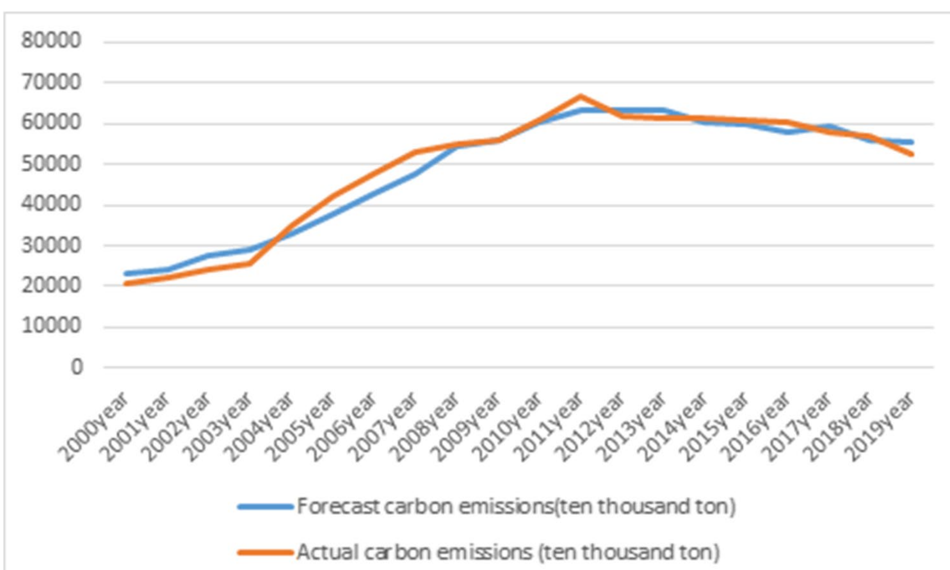

Fig. 2 Fitting diagram of analog value and actual value

Standard development scenario: all indicators are carried out at the current set speed, with moderate speed of industrial structure adjustment, energy structure optimization, and energy intensity adjustment.

High-speed development scenario: the adjustment of industrial structure is slow, and the decline of secondary industrial structure with high carbon emissions is slow. In the energy structure, the proportion of coal decreases slowly; Slow decline of energy intensity; Etc.

Low-carbon scenario: the industrial structure has been adjusted rapidly, and the energy consumption level and energy intensity of key high carbon industries have decreased significantly.

Trend analysis

Based on the parameters of each variable under three different scenarios, the STIRPAT model is used to fit and predict the carbon emissions of Henan Province from 2020 to 2040. The results are shown in Fig. 3.

From Fig. 3, we can see that (1) the low-carbon development scenario has reached the inflection point of the carbon peak. If Henan Province develops according to the low-carbon development scenario, the carbon emissions will continue to decline, and will achieve the goal of "carbon neutrality" by 2060; that is, the carbon emissions and carbon emission reduction in Henan Province will be offset positively and negatively. (2) Under the standard development scenario, the carbon emissions of Henan Province will change from growth to stability around 2020 and begin to show an obvious downward trend around 2030. (3) Under the scenario of high-speed development, the carbon emissions of Henan Province will increase from 2020 to 2035, and will not become stable and show a slow downward trend until 2035. (4) The high-speed development scenario focuses on economic development, and the control of carbon emissions is not strong enough to reach the "carbon peak" goal by 2030. (5) The low-carbon development scenario focuses on the development of green economy, and the economic growth is relatively slow. Staying in this scenario is not conducive to economic development. (6) The standard development scenario not only focuses on energy conservation and emission reduction, but also develops the economy, and the two are in a balanced state of development.

Research conclusion

This paper combines Tapio decoupling model, Kaya identity, and LMDI decomposition model to explore the decoupling relationship between carbon emissions and economic growth in Henan Province from 2000 to 2019. The influencing factors of carbon emissions are decomposed into five effects: carbon emission intensity effect, energy structure effect, energy intensity effect, economic level effect, and population effect, so as to explore the driving factors of carbon emissions. In order to explore the carbon emission trend of Henan Province from 2020 to 2034, this paper constructs the STIRPAT model and sets up three development scenarios (high speed, standard, and low carbon) to simulate and predict the carbon emission of Henan Province in combination with the scenario analysis method.

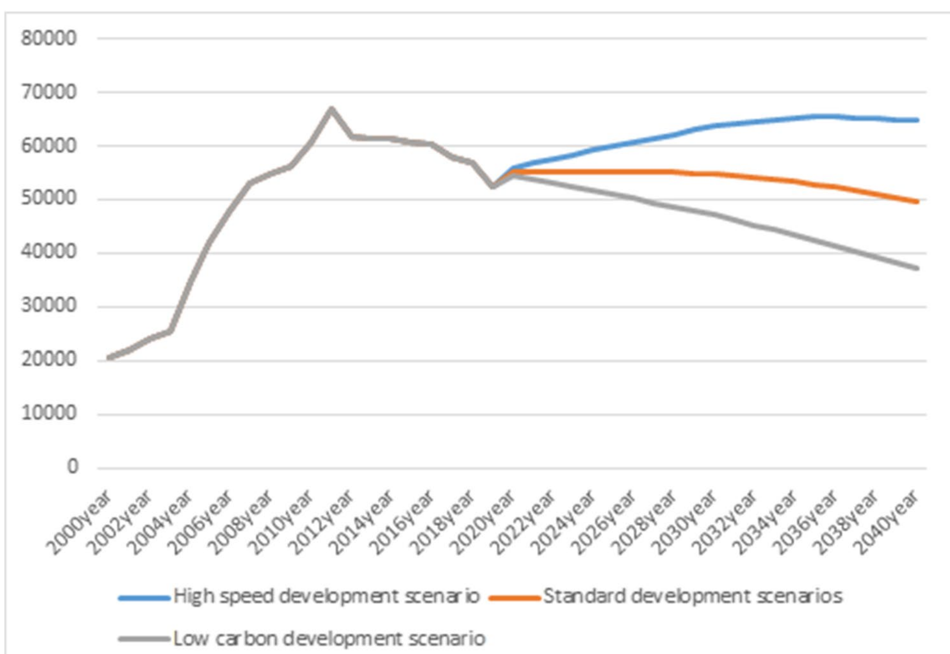

Fig. 3 Carbon emission prediction of STIRPAT model

Through the construction and analysis of the above model, this paper draws the following conclusions:

1) From 2000 to 2019, in general, there was a weak decoupling between carbon emissions and economic growth in Henan Province, indicating that the economic growth of Henan Province was faster than that of carbon emissions, and it was in an ideal development state. This is similar to the research results of Sun Xin (2022) and Liu Qi-tao (2014).
2) The LMDI decomposition model is used to decompose the elastic factors between carbon emissions and GDP growth in Henan Province. Conclusion: the overall elasticity coefficient of economic level effect is 0.647, which has a significant inhibitory effect on Tapio elasticity coefficient. The overall elastic coefficient of energy intensity effect is − 0.239, which can promote the decoupling of Henan Province. The overall elasticity coefficient of energy structure effect is − 0.003, which can promote the decoupling of Henan Province. The overall elasticity coefficient of population effect is 0.012, which inhibits the overall elasticity coefficient of Henan Province. The fluctuation of energy intensity effect is basically synchronized with the elasticity coefficient, and the change of other effects is small. Therefore, if Henan Province wants to maintain a strong decoupling state, the energy consumption and GDP should show a downward and increasing trend, respectively, so that the energy intensity effect can reach the highest. This is similar to (Guo et al. 2019) research on the impact of economic level, energy intensity, energy structure, and population equivalence on Tapio's elasticity coefficient.
3) Establishing STIRPAT model to study the influencing factors of carbon emissions in Henan Province, and predict carbon emissions, except that the energy structure and carbon emission intensity have a negative impact on carbon emissions, other factors have a positive impact. The low-carbon development scenario has reached the inflection point of the carbon peak. Under the standard development scenario, the carbon emissions of Henan Province will change from growth to stability around 2020 and begin to show an obvious downward trend around 2030. Under the scenario of high-speed development, the carbon emissions of Henan Province will increase from 2020 to 2035, and will not become stable and show a slow downward trend until 2035. The standard development scenario is more suitable for the development of Henan Province, so Henan Province should maintain the current development momentum. If Henan Province wants to accelerate to achieve "carbon neutrality", it can adopt the low-carbon development scenario in an appropriate period. This is similar to Guo Y and Li J et al. (2016), Huang R and Wang Z et al. (2012), and Zhang P and He J et al. (2017) in terms of the impact of energy intensity, carbon emission intensity, population and other factors on carbon emissions, and the prediction results of carbon emissions and carbon peaks.

Proposal

In order to make Henan Province achieve the goals of "carbon neutralization" and "carbon peak" as soon as possible, and find out a suitable green development path, based on the above research conclusions, this paper puts forward the following suggestions and measures:

Reduce the proportion of coal energy and increase the proportion of new energy

In 2019, coal consumption in Henan Province accounted for 66.6% of the total energy structure, while new energy such as natural gas accounted for a relatively low proportion. According to the research of Tapio decoupling model, optimizing the energy structure can make Henan Province move towards a strong decoupling state—the optimal development state. Therefore, Henan Province should actively optimize the energy structure, vigorously promote the measures of energy conservation and emission reduction, and push the energy supply to the direction of diversified development. It is mainly to control the total consumption of fossil energy such as coal and strive to increase the proportion of new energy such as natural gas and wind energy, encourage the use of new energy vehicles, and add wind power and photovoltaic power generation machines.

Optimize the industrial structure and reduce the proportion of the secondary industry

According to the results of STIRPAT model, the industrial structure of Henan Province has a positive relationship with carbon emissions, and the secondary industry of Henan Province is the main industry of coal consumption. Therefore, in order to achieve the goals of "carbon peaking" and "carbon neutralization", Henan Province should reduce the proportion of the secondary industry. Henan Province should transform from a traditional agricultural and industrial province to a cultural and tourism province, such as use technical means to integrate into the innovative development model; combine nature, humanity, and VR and AR technologies; and create a distinctive cultural tourism brand; develop creative products that people like to see and enjoy in various links such as food, housing, transportation, travel, shopping, and entertainment to promote the restructuring and integration of cultural tourism industry.

Build a new type of city and rationally urbanize

The urbanization rate has a positive impact on carbon emissions, and Henan Province plans to reach 60% of the permanent population by 2025, which will further lead to an increase in carbon emissions. In order to realize the win–win situation of "carbon peak", "carbon neutralization", and urban planning in Henan Province, Henan Province should build a new type of green city, so that people can have a high-level and high-quality urban life and accept green life to reduce carbon emissions. Rely on innovative elements such as science and technology, knowledge, human resources, culture, and system to drive development and improve the quality of the citizenization of the agricultural transfer population, enhance the comprehensive carrying capacity of central cities and urban agglomerations, and optimize the allocation of resources, and promote the construction of new urbanization with county towns as an important carrier.

Strengthen scientific and technological research and development to ensure sustainable economic development

Henan Province should strengthen the research and development of clean energy alternative technologies, renewable energy technologies, and new energy technologies, so as to improve the energy utilization rate of enterprises, meet the decomposition and emission reduction requirements from the production chain to the whole use cycle, ensure the transformation effect, and reduce excessive waste of resources. This can not only reduce carbon emissions, but also ensure the rapid economic growth of Henan Province.

Waste gas utilization to promote economic development

Henan Province can collect the carbon dioxide produced by industry, and use its characteristics of promoting plant growth, absorbing a large amount of heat, and copolymerization with epoxides to convert it into harmless and beneficial products such as carbon fertilizer, dry ice agent, and new synthetic materials by using clean technology, so as to realize the utilization of waste gas.

Establish a carbon emission exchange and improve the trading market for carbon emissions

At present, China has begun to gradually implement the development goal of carbon emission allocation and has established Beijing carbon emission exchange and Shanghai carbon emission exchange. Henan Province should also establish a carbon emission exchange, formulate the carbon emission quota of each unit, publish the relevant information of the carbon emission trading market, and strengthen the risk control and internal supervision and management of trading activities to standardize the carbon emission trading between enterprises in Henan Province, which can not only curb the phenomenon of enterprises' random emission of exhaust gas, but also further promote the economic development of Henan Province.

Author contribution "Decoupling relationship between carbon emissions and economic development and prediction of carbon dioxide emissions in Henan Province: Based on Tapio method and STIRPAT model" is the result of the joint efforts of the three of us, so after discussion, we decided to publish this article as the co first author.

The following is the contribution of each member:

Zhengqi Wei: Develop overall objectives and select appropriate research methods; Write first draft; Supervise; Article management.

Keke Wei: Data collection; Write first draft; Project implementation and coordination.

Jiincheng Liu: Data processing; Review and editing; Data comparison and analysis.

Data availability The datasets generated during and/or analyses during the current study are not publicly available due to [REASON(S) WHY DATA ARE NOT PUBLIC] but are available from the corresponding author on reasonable request.

Declarations

Ethical approval This article does not involve human participants or animal research. There is no behavior that does not conform to the ethical standards.

Consent to participate All authors agree with the contributions of each author in this article, and there is no dispute.

Consent to publish All authors have agreed to publish this paper.

Competing interests The authors declare no competing interests.

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