

Carbon Emission Measurement and the Decoupling Effect Under the “Double Carbon” Goal in Xi’an, China

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Abstract Cities generate more than 60% of carbon emissions and are the main battleground for achieving the target. However, there is no unified and standardized measurement methods of carbon emissions in cities. In this paper, we took Xi’an as an example and started by measuring carbon emissions with the new standards. Then, the decoupling of economic development from carbon emissions was studied according to the Tapio decoupling theory. Based on the generalized Divisia index method, the decoupling effort model was proposed to study the impact of carbon emission factors contributing to carbon reduction. The results show: (i) During the period 1995–2021, the carbon emissions of Xi’an increased rapidly, with an average annual growth rate of 6.06%, due to the accelerating pace of urbanization and industrialization. (ii) The energy consumption sector accounted for the largest share of carbon emissions, ranging from 77.38% to 89.46%. Xi’an’s energy structure is primarily based on fossil fuels, especially coal, which holds a significant proportion. To achieve the “double carbon” goal, it is crucial to reduce the dependence on fossil fuels. (iii) The 10th Five-Year Plan was in the state of “expansive coupling”, while other periods were in the “weak decoupling” state from the 9th to 14th Five-Year Plan periods. After the carbon peak year in the 15th Five-Year Plan, it would be in a state of “strong decoupling”. The agricultural production account was the first to achieve a “strong decoupling” state. (iv) The government of Xi’an made efforts to decouple, but these were not enough. Technological innovation played a crucial role in the carbon reduction of Xi’an, and was a key factor in achieving the “double carbon” goal.

Keywords “double carbon” goal; city carbon emission measurement; economic growth; decoupling

1 Introduction

Global climate change, characterized by climate warming, has become one of the most serious challenges facing humanity in the 21st century, posing a long-term threat to food security, water security, environmental security, infrastructure security, and the safety of public life and property^[1]. In 2015, the Paris Agreement set a long-term temperature goal of holding the global average temperature increase to below 2°C and pursuing efforts to limit this to 1.5°C on the pre-industrial levels^[2,3]. Faced with the serious problem of climate warming, the Chinese government has taken on the responsibility of a great nation and set the goal of “achieving

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carbon peak by 2030 and carbon neutrality by 2060” (“double carbon” goal). Therefore, the CPC Central Committee and the State Council issued *Opinions on the Complete and Accurate Implementation of the New Development Concept to Do a Good Job in Carbon Peaking and Carbon Neutral Work*^[4], and approved *Action Plan for Carbon Dioxide Peaking Before 2030*^[5]. Nine ministries of China, including the Ministry of Science and Technology, issued the *Science and Technology to Support the Implementation Plan of Carbon Peak and Carbon Neutrality (2022–2030)*^[6]. The Chinese government is taking concrete steps to ensure that the “double carbon” goal will be achieved on time. Cities are the main gathering place of humans, the center of economic activity, and the main carrier of energy consumption. Cities produce more than 60% of carbon emissions and are the main battleground for achieving carbon peak and carbon neutrality^[7,8]. If cities fail to achieve carbon peak, it would be difficult to achieve the carbon peak goal on time, which in turn will hinder the low-carbon and high-quality development of China^[9]. Therefore, urban carbon peak is a necessary condition for achieving the “double carbon” goal.

In the context of the “double carbon” goal, the measurement of urban carbon reduction and its influencing factors have become a hot topic of current academic research. Currently, there is no unified and standardized measurement methods of carbon emissions in cities. This mainly includes^[10]: *International Standard for Determining Greenhouse Gas Emissions for Cities*, *Local Government Greenhouse Gas Emissions Analysis Protocol*, *The 2006 IPCC Guidelines for National Greenhouse Gas Inventories* and *Guidelines for the Preparation of Provincial Greenhouse Gas Inventories in China* etc. Due to the late start of emission inventory research in Chinese cities, most existing urban emission inventories are based on existing international urban emission guidelines. Bai^[11] considered the *Guidelines for the Preparation of Provincial Greenhouse Gas Inventories in China* and *International Local Government Greenhouse Gas* as important references for the study of urban greenhouse gas emissions inventories in China, and calculated the greenhouse gas emissions of Guangyuan, a city in Sichuan Province. However, current research has yet to adequately address the capital cities of western provinces in China.

The issue of carbon reduction in China has received a great deal of attention from the academic community, particularly the discussion on how to achieve the “double carbon” goal. It has been generally agreed that technological progress^[12], energy efficiency improvement^[13], and industrial restructuring^[14] are the main drivers of carbon reduction. It is linked to achieving the “double carbon” goal and to economic development. Achieving the “double carbon” goal is not only about carbon reduction, but also about sustaining economic development to protect the country’s livelihood, which is both an opportunity and a challenge to promote high-quality urban development^[15–17]. In recent years, the accelerated rate of urbanization in China had a significant impact on carbon emissions^[18]. The focus of the existing research has primarily been on the efforts and influencing factors to the national or regional carbon emissions reduction, while there is a relative lack of research on the effects to urban carbon reduction efforts.

Based on the above, this paper may contribute in the following aspects: Firstly, it explores the methodology for the measurement of carbon emissions in Chinese cities according to the new standard. Xi’an, the capital of Shaanxi province in western China, is chosen as the research object. The carbon emissions are measured based on the 2019 *Refinement to the 2006*

IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2019) and *Guidelines for the Preparation of Provincial Carbon Emission Peaking Action Plans*. Secondly, the decoupling effect of urban carbon emissions from economic development is analyzed. It explores the relationship between urban economic development and carbon reduction in the context of the “double carbon” goal. Based on the source of carbon emissions accounts, analyze which sectors have not yet decoupled from carbon emissions and which have already achieved decoupling, providing a decision-making basis for targeted decoupling measures. Thirdly, it analyses the factors influencing the decoupling effect. Science and technology innovation (STI) is integrated with other factors in the study to analyze the role of STI in supporting the “double carbon” objective. The remainder of this paper is organized as follows: Section 2 reviews the existing literature. Section 3 introduces the research methods. Section 4 presents the results and discussion. Section 5 presents the conclusions.

2 Literature Review

2.1 Carbon Emission Measurement Methods

There are mainly three methods for measuring carbon emissions: The input-output (IO) method, the lifecycle (LC) method, and the GHG emission inventory method of the Intergovernmental Panel on Climate Change (IPCC method). First, the IO method. The IO method has been widely used to assess the environmental impact of socio-economic activities based on IO tables^[19]. In theory, the IO method reflects the IO relationship among sectors in the economy. It allows the estimation of direct and indirect emissions by industry sector and final demand to be estimated at a disaggregated level^[20]. The IO method has been widely used in carbon emissions studies since the introduction of the environmentally extended IO framework. See, for example, Zeshan^[21], Yang, et al.^[22], Mastronardi, et al.^[23], and Jiang, et al.^[24]. However, the IO method has certain limitations for measuring carbon emissions. The IO tables are updated every five years in China, and it may take longer for the local governments to update the IO data. In addition, the conversion of monetary values into emissions may introduce uncertainties.

Second, the LC method. The LC method is an objective and quantitative assessment index, which mainly evaluates the GHG emissions generated by a product in a series of processes from production, processing, and use^[25–27]. Chen, et al.^[28] believed that the life cycle method had become the main measurement method for carbon footprints at the micro level, and is mainly applied to measure carbon emissions generated by the production process of products. The construction industry, as one of the high carbon-emitting industries, has become an important domain for the LC method. Xu, et al.^[29] divided the life cycle of a space frame structure into four phases including component production, construction, maintenance, and demolition. Khandelwal, et al.^[30] applied the life cycle method in municipal solid waste management. The disadvantage of the LC method is that it is difficult to obtain accurate data, making it less adaptable to regional carbon emissions.

Third, the IPCC method. The data for the IPCC method is relatively easy to obtain compared to the two methods mentioned above^[31,32]. The IPCC 2019 was adopted and accepted during the 49th Session of the IPCC in May 2019. In 2021, China’s Ministry of Ecology and

Environment^[33] issued *Guidelines for the Preparation of Provincial Carbon Emission Peaking Action Plans*, which was based on the IPCC guidelines and made some additions according to the situation in China. The IPCC method can be flexibly adapted to the characteristics of the study object. It could therefore be applied to a wide range of regions or specific sectors. Xi, et al.^[34] evaluated the GHG emissions for Shanghai municipal wastewater treatment plants based on IPCC. Wu, et al.^[35] examined the allocation of carbon emission rights in China’s six high-energy-consuming industries from the perspective of allocation efficiency under the IPCC limits. Zhao, et al.^[36] analyzed the GHG emission and evaluated the extent of emissions in Xi’an according to IPCC 2006.

2.2 Decoupling of Economic Development from Carbon Emissions

Many researchers have used the decoupling theory to investigate whether economic development depends on energy consumption^[37,38], urban water use^[39,40], coal consumption^[41–43], and GHG emissions^[44,45]. The relationship between carbon emissions and economic development has received a great deal of attention, and the scope of the research is spread across different industries in different countries. Moreau and Vuille^[46] distinguished the decoupling state into real and virtual decoupling. Real decoupling occurs as a result of effective reductions in energy consumption or energy efficiency measures in economic activities and households. However, virtual decoupling occurs due to changes in the structure of the economy, such as increased reliance on imports, which reduces domestic energy consumption by exporting energy abroad, thereby significantly reducing energy intensity. To quantify the effectiveness of energy efficiency measures in reducing energy consumption, Moreau, et al.^[47] analyzed the underlying nature of decoupling in the European Union from 1990 to 2014. Wang and Jiang^[48] took BRICS (Brazil, Russia, India, China, and South Africa) as an example to investigate the decoupling state between economic development and carbon emissions, aiming to uncover the driving factors behind the decoupling. Rao, et al.^[49] set up a methodology of correlation effects decoupling index to discover the decoupling status and studied the decoupling of economic growth from carbon emissions in Yangtze River Economic Belt sectors. Based on Tapio decoupling theory, Chen, et al.^[50] analyzed the decoupling effects of 284 cities in China from 2005 to 2019, and aggregated the cities into four groups according to the decoupling effects.

Frankly, the above literature has contributed to decoupling economic growth from carbon emissions in cities and regions, but there is still a lack of discussion on decoupling efforts^[51]. The decoupling method, known as the Tapio model, has been used to analyze the relationship between economic development and carbon emissions. We might know whether the economy in a region is decoupled from carbon emissions. However, it is impossible to know which factors contributed to these observations. Therefore, it is necessary to study the impact of each factor contributing to carbon reduction. There was a lack of research, especially for Xi’an. Huang and Tian^[52] studied the carbon emission influencing factors of Xi’an based on GDIM and simulated the carbon emissions from 2021–2060 according to the technology breakthrough scenarios.

3 Methods

3.1 Carbon Emission Measurement Based on New Standards

According to *IPCC 2019* and *Guidelines for the Preparation of Provincial Carbon Emission Peaking Action Plans*, carbon emissions (CD , 10^4 t) of Xi'an are measured by sectors of energy consumption (CF_E), industrial process (CF_P), waste disposal (CF_W), agricultural production (CF_L), and forestry and other land use (CC), respectively. It is calculated as follows:

$$CD = (CF_E + CF_P + CF_W + CF_L) - CC. \quad (1)$$

3.1.1 Energy Consumption Sector

Carbon emissions (CF_E) of the energy consumption sector includes two parts: direct emission of fossil energy (CF_{E_1}) and indirect emission of electricity (CF_{E_2}).

1. Fossil energy consumption

The emissions of fossil energy consumption (CF_{E_1}) is accounted by IPCC type I, which is composed of industrial production consumption ($CF_{E_1}^P$), residential consumption ($CF_{E_1}^R$) and vehicle energy consumption ($CF_{E_1}^V$).

In industrial production consumption, the carbon emissions from the combustion of fossil energy ($CF_{E_1}^P$, mainly refers to the production of industrial enterprises above the scale) is calculated as follows:

$$CF_{E_1}^P = \sum_i \left(AC_i \times NCV_i \times EF_i \times COF_i \times \frac{44}{12} \times 10^{-3} \right), \quad (2)$$

where, AC_i is the consumption of the i th fuel (10^4 t or 10^8 m³). NCV_i is the low-level calorific value of the i th fuel (TJ/Gg). EF_i is the carbon content per unit calorific value of the i th fuel (tC/TJ). COF_i is the carbon oxidation rate of the i th fuel. $44/12$ is the molecular ratio of CO_2/C . 10^{-3} is the unit conversion factor. According to the *Xi'an Statistical Yearbook*, the fuel of industrial production mainly includes the following 15 types: Raw coal, washed coal, other washed coal, coal products, coke, other coking products, coke oven gas, natural gas, liquefied natural gas, crude oil, gasoline, kerosene, diesel, fuel oil, liquefied petroleum gas.

Residential living consumption fuels of Xi'an mainly include: Gas, natural gas, liquefied petroleum gas, and carbon emissions ($CF_{E_1}^R$) reference equation (2).

The carbon emissions ($CF_{E_1}^V$) of the vehicle are calculated as follows:

$$CF_{E_1}^V = \sum_i \left(VP_i \times VMT_i \times FE_{ig/d} \times EF_{g/d} \times \rho_{g/d} \times \frac{44}{12} \times 10^{-4} \right), \quad (3)$$

where, VP_i is the number of i th type vehicles. Given the availability of data and the relatively low number of new energy vehicles in Xi'an, no distinction is made between fuelled vehicles and new energy vehicles. VMT_i is the average annual mileage of the i th type of vehicle (10^3 km/vehicle). $FE_{ig/d}$ is the fuel economy of the i th type of vehicle (L/km). $EF_{g/d}$ is the carbon emission factor. g/d indicates the type of vehicle fuel, g is gasoline, d is diesel. $\rho_{g/d}$ is the density. $44/12$ is the molecular weight ratio of CO_2/C . 10^{-4} is the unit conversion factor.

2. Indirect emissions from electricity

The method of accounting for indirect emissions (CF_{E_2}) from electricity transfers (power dispatch, transfer-in is positive and transfer-out is negative) is as follows:

$$CF_{E_2} = AC_P \times Q \times 10, \quad (4)$$

where, AC_P is the difference between transfer-in and transfer-out (10^8 kW·h). Q is the average carbon emission factor (kg/kW·h) of the regional grid electricity supply, and the default value for the area where Xi'an located is 0.997. 10 is the unit conversion factor.

3.1.2 Industrial Process Sector

The industrial process (CF_P) only calculates the CO_2 generated during the conversion of raw materials into silicate cement clinker in the cement production process. CO_2 released from the combustion of fuels in industrial process is already included in the energy consumption. It is calculated as follows:

$$CF_P = PO \times d, \quad (5)$$

where, PO is the silicate cement clinker consumption (10^4 t); d is the CO_2 released during the decomposition of silicate cement clinker (per ton).

3.1.3 Waste Disposal Sector

The first-order decay method is used to account for GHG releases from waste disposal^[53], which mainly includes CO_2 , CH_4 and N_2O generated from municipal solid waste and wastewater treatment processes.

$$CF_W = 25CF_{W1} + 25CF_{W2} + 298CF_{W3}, \quad (6)$$

where, CF_{W1} is the emissions of CH_4 from the solid waste disposal process (10^4 t). CF_{W2} and CF_{W3} are the emissions of CH_4 and N_2O produced in the waste water treatment process, respectively (10^4 t). 25 is the global warming potential (GWP) of CH_4 and 298 is the GWP of N_2O .

1. Municipal solid waste disposal

Municipal solid waste in Xi'an mainly includes domestic and industrial solid waste, and the disposal of municipal solid waste has been mainly landfilled in the past years. CH_4 emissions from landfill disposal (CF_{W1}) is calculated as:

$$CF_{W1} = \left(\sum_i W_i \times DOC_i \times DOC_F \times MCF \times F \times \frac{16}{12} - R \right) (1 - OX), \quad (7)$$

where, W_i is the disposal volume of the i th solid waste (10^4 t). DOC_i is the i th solid waste degradable organic carbon (tC/t waste). DOC_F is the proportion of DOC that can be decomposed under anaerobic conditions. MCF is the correction factor of CH_4 . F is the volume fraction of CH_4 in total gas produced by the landfill. $16/12$ is the molecular weight ratio of CH_4/C . R is the amount of CH_4 recovered (10^4 t). OX is the oxidation factor.

2. Wastewater disposal

The wastewater disposal process mainly accounts for CH₄ and N₂O emissions. CH₄ emissions (CF_{W2}) are calculated as follows:

$$CF_{W2} = T \times B_0 \times MCF - R, \quad (8)$$

where, T is the total amount of biochemical oxygen demand (BOD) discharged in the wastewater (10^4 BOD), which is obtained by multiplying the average value of BOD/COD with the COD removed from wastewater of Xi'an in previous years. B_0 is the maximum production capacity of CH₄. MCF is the correction factor of CH₄. R is the recovery of CH₄ (10^4 t).

The N₂O emissions from the wastewater disposal process (CF_{W3}) are calculated as follows:

$$CF_{W3} = (P \times P_r \times F_{NPR} \times F_{NON-CON} \times F_{IND-CON} - N_S) \times EF_E \times \frac{44}{28} \times 10^{-7}, \quad (9)$$

where, P is the total population (10^4 persons). P_r is the annual per capita protein consumption (kg/person). F_{NPR} is the nitrogen content in protein (kg/kg protein). $F_{NON-CON}$ is the non-consumed protein factor in wastewater. $F_{IND-CON}$ is the protein emission factor for industry and commerce. N_S is the nitrogen removed with sludge (kgN). EF_E is the N₂O emission factor for wastewater (kgN₂O/kgN). $44/28$ is the molecular weight ratio of N₂O/N₂. 10^{-7} is the unit conversion factor.

3.1.4 Agricultural Production Sector

According to the characteristics of agricultural production in Xi'an, the GHG emissions mainly come from CH₄ emissions (CF_{L1}) of rice fields, CH₄ emissions (CF_{L2}) of animal intestinal fermentation, CH₄ emissions (CF_{L3}) and N₂O emissions (CF_{L4}) of animal manure management process, and N₂O emissions of agricultural land (CF_{L5}).

$$CF_L = 25(CF_{L1} + CF_{L2} + CF_{L3}) + 298(CF_{L4} + CF_{L5}). \quad (10)$$

1. Rice field

CH₄ emissions (CF_{L1}) in rice fields are calculated as:

$$CF_{L1} = \sum_i EF_i \times AD_i \times 10^{-3}, \quad (11)$$

where, EF_i is the CH₄ emission factor (kg/hm²) of the i th type of rice field. AD_i is the sown area (hm²) of the i th type rice field. 10^{-3} is the unit conversion factor.

2. Animal intestinal fermentation

Animal intestinal fermentation CH₄ emissions (CF_{L2}) are calculated as:

$$CF_{L2} = \sum_i EF_i \times AP_i \times 10^{-3}, \quad (12)$$

where, EF_i is the CH₄ emission factor of the i th type animal (kg/head). AP_i is the number of the i th type animal (head). 10^{-3} is the unit conversion factor.

3. Animal manure management process

Animal manure management process CH_4 emissions (CF_{L3}) and N_2O emissions (CF_{L4}) are calculated as follows:

$$CF_{L3/L4} = \sum_i EF_i \times AP_i \times 10^{-3}, \quad (13)$$

where, EF_i is the CH_4 or N_2O emission factor (kg/head) of the i th type animal. AP_i is the number of the i th type animal (head). 10^{-3} is the unit conversion factor.

4. Agricultural land

N_2O emissions from agricultural land include both direct emissions (CF_{L5}^D) and indirect emissions (CF_{L5}^I).

(1) Direct emissions

Direct agricultural N_2O emissions are calculated as follows:

$$CF_{L5}^D = N_{in} \times EF = (N_e + N_m + N_s) \times EF, \quad (14)$$

where, N_{in} is the total N input to agricultural land (10^4 tN). N_e is fertilizer N (10^4 tN). EF is the direct emission factor (kg $\text{N}_2\text{O}-N$ /kg N_{in}). N_m is manure N (10^4 tN), and it is calculated as:

$$N_m = [(N_t - N_g - N_f) + N_p](1 - LR - VR) - N_{lp}, \quad (15)$$

where, N_t is total N excretion from livestock. N_g is N excretion during grazing. N_f is N excretion from fuel consumption. N_p is total N excretion from the rural population. LR is the loss rate of leaching runoff. VR is the volatilization loss rate. N_{lp} is N_2O emission from livestock closed management system.

N_S is straw return N (10^4 tN), which consists of aboveground straw return N (N_S^U) and underground root N (N_S^D). Aboveground straw return N (N_S^U , 10^4 tN) is calculated as follows:

$$N_S^U = \sum_i (Y_i/E_i - Y_i) \times R_{Si} \times R_{Ni}, \quad (16)$$

where, Y_i is the seed yield of the i th crop (10^4 t), and the main crops in Xi'an include wheat, corn, rice, and rapeseed. E_i is the economic coefficient of the i th crop. R_{Si} is the straw return rate of the i th crop. R_{Ni} is the N content of the i th crop's straw.

Underground root N (N_S^D , 10^4 tN) is calculated as:

$$N_S^D = \sum_i Y_i/E_i \times R_{Si} \times R_{Ni}, \quad (17)$$

where, R_{Si} is the root-to-crown ratio, and the rest of the symbols are interpreted as in equation (15).

(2) Indirect emissions

Indirect N_2O emissions from agricultural land (CF_{L5}) consist of indirect emissions due to atmospheric N deposition (CF_{L5}^{I1}) and leaching runoff (CF_{L5}^{I2}). Indirect emissions of N_2O due to atmospheric N deposition (CF_{L5}^{I1}) are calculated as follows:

$$CF_{L5}^{I1} = N_t \times 0.2\% + N_{in} \times 0.1\%, \quad (18)$$

where, N_t is livestock manure (10^4 tN). N_{in} is total N input to agricultural land (10^4 tN).

Indirect N_2O emissions (CF_{L5}^{I2}) due to leaching runoff from agricultural fields are calculated as:

$$CF_{L5}^{I2} = N_{in} \times 1.5\%, \quad (19)$$

where, N_{in} is the total N input to the agricultural land (10^4 tN).

3.1.5 Forestry and Other Land Use Sector

The carbon sequestration capacity of various green vegetation in Xi'an is mainly composed of forest (CC_F), grassland (CC_G) and crop (CC_P) sequestration capacity.

1. Forest and grassland

The carbon sequestration capacity of forest and grassland (10^4 tC) is calculated as follows:

$$CC_{F/G} = AD_{F/G} \times NEP_{F/G}, \quad (20)$$

where, F and G denote forest and grassland, respectively. $AD_{F/G}$ is the total area of forest or grassland (10^4 hm²). $NEP_{F/G}$ is the average carbon sequestration capacity of forest or grassland (tCO₂/hm²).

2. Crops

The carbon sequestration capacity of crops (10^4 tC) is calculated as:

$$CC_P = \left(\sum_i \frac{Y_i (1 - \omega_i)}{E_i} \right) \times \lambda \times z \times \frac{44}{12}, \quad (21)$$

where, Y_i is the yield of the i th crop (10^4 t), and the crops for calculating carbon sequestration capacity include wheat, corn, rice, canola, and vegetables. ω_i is the water content of the i th crop. E_i is the economic coefficient of the i th crop. λ is the correction factor. z is the coefficient of biomass and carbon conversion. $44/12$ is the molecular weight ratio of CO₂/C.

3.2 Decoupling and Decoupling Effort Model

3.2.1 Tapio Decoupling Model

Economic growth is the most significant positive factor affecting carbon emissions^[54]. Therefore, it is necessary to study the correlation between economic growth and carbon emissions. The most widely used method for studying the relationship between carbon emissions and economic development is the Tapio model. The Tapio decoupling model is based on the elasticity of material consumption and uses the elasticity value to analyze the relationship between environmental pressure and economic development. It is calculated as follows:

$$E_{CO_2, GDP} = \frac{(CO_{2,t} - CO_{2,0}) / CO_{2,0}}{(GDP_t - GDP_0) / GDP_0}, \quad (22)$$

where, CO₂ is the environmental pressure, i.e., carbon emissions. GDP represents economic development, i.e., gross domestic product. The subscript t is the target period, where 0 is the base period.

According to the range of elasticity values, the decoupling states are classified into 8 types of state: Expansive negative decoupling, strong negative decoupling, weak negative decoupling, weak decoupling, strong decoupling, recessive decoupling, expansive coupling, recessive coupling, corresponding to different situations of carbon emissions and economic development^[55]. The decoupling types are obtained as shown in Table 1. The Tapio decoupling model can identify different combinations of environmental pressure and economic development. The Tapio decoupling model can identify different combinations of environmental pressure and economic development, and thus provide a reference for decision-making on related policies.

Table 1 Categorization of decoupling status

Decoupling State		Parameters	Description	Value
Negative decoupling	Expansive negative decoupling	> 0	> 0	> 1.2
	Strong negative decoupling	> 0	< 0	< 0
	Weak negative decoupling	< 0	< 0	$0 < E < 0.8$
Decoupling	Weak decoupling	> 0	> 0	$0 < E < 0.8$
	Strong decoupling	< 0	> 0	< 0
	Recessive decoupling	< 0	< 0	> 1.2
Coupling	Expansive coupling	> 0	> 0	$0.8 < E < 1.2$
	Recessive coupling	< 0	< 0	$0.8 < E < 1.2$

3.2.2 Decomposition Model of Carbon Emissions

Based on the GDIM decomposition model, Huang and Tian^[52] studied the influencing factors on carbon emissions, including economic output (GDP), output carbon intensity (OCI), energy consumption (EC), energy consumption carbon intensity (ECCI), science and technology innovation investment (STII), science and technology innovation investment carbon intensity (STIICI), population (P), CO_2 per capita (CPC), science and technology innovation investment efficiency (STIICI), energy intensity(EI). GDIM is based on the Kaya identity to construct a multifactor decomposition model. According to GDIM^[56], the factors influencing carbon emissions in Xi'an are decomposed as follows:

$$\text{CO}_2 = (\text{CO}_2/\text{GDP}) \times \text{GDP} = (\text{CO}_2/E) \times E = (\text{CO}_2/P) \times P = (\text{CO}_2/T) \times T, \quad (23)$$

$$\text{GDP}/T = (\text{CO}_2/T)/(\text{CO}_2/\text{GDP}), \quad (24)$$

$$E/\text{GDP} = (\text{CO}_2/\text{GDP})/(\text{CO}_2/E). \quad (25)$$

The symbols in Eqs. (23)~(25) are defined in Table 2.

Further transformation of Eqs. (23)~(25) yields:

$$Z = X_1 X_2, \quad (26)$$

$$X_1 X_2 - X_3 X_4 = 0, \quad (27)$$

Table 2 The acronyms and variables involved in GDIM

Acronyms	Meaning	Variables
CE	Carbon emissions	$Z = CO_2$
GDP	Economic output (GDP)	$X_1 = GDP$
OCI	Output carbon intensity	$X_2 = CO_2/GDP$
EC	Energy consumption	$X_3 = E$
ECCI	Energy consumption carbon intensity	$X_4 = CO_2/E$
STII	Science and technology innovation investment	$X_5 = T$
STIICI	Science and technology innovation investment carbon intensity	$X_6 = CO_2/T$
P	Population	$X_7 = P$
CPC	CO_2 per capita	$X_8 = CO_2/P$
STIIE	Science and technology innovation investment efficiency	$X_9 = GDP/T$
EI	Energy intensity	$X_{10} = E/GDP$

$$X_1 X_2 - X_5 X_6 = 0, \quad (28)$$

$$X_1 X_2 - X_7 X_8 = 0, \quad (29)$$

$$X_1 - X_5 X_9 = 0, \quad (30)$$

$$X_3 - X_1 X_{10} = 0. \quad (31)$$

According to the GDIM theory, the gradient of the contribution function $Z(X)$ and the Jacobian matrix could be obtained as follows:

$$\nabla Z = \langle X_2, X_1, 0, 0, 0, 0, 0, 0, 0, 0 \rangle^T \quad (32)$$

$$\Phi_X = \begin{bmatrix} X_2 & X_1 & -X_4 & -X_3 & 0 & 0 & 0 & 0 & 0 & 0 \\ X_2 & X_1 & 0 & 0 & -X_6 & -X_5 & 0 & 0 & 0 & 0 \\ X_2 & X_1 & 0 & 0 & 0 & 0 & -X_8 & -X_7 & 0 & 0 \\ 1 & 0 & 0 & 0 & -X_9 & 0 & 0 & 0 & -X_5 & 0 \\ -X_{10} & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & -X_1 \end{bmatrix}. \quad (33)$$

Then, ΔZ can be decomposed into the sum of the contributions from each factor:

$$\Delta Z[X | \Phi] = \int_L \nabla Z^T (I - \Phi_X \Phi_X^+) dX, \quad (34)$$

where, L is the time range from t_0 to t_1 . I is the identity matrix. Φ_X^+ is the generalized matrix of Φ_X . If the columns of Φ_X are linearly independent, then $\Phi_X^+ = (\Phi_X^T \Phi_X)^{-1} \Phi_X^T$.

3.2.3 Decoupling Effort Model

GDIM is mainly used to study the drivers of changes in carbon emissions, but this method is limited to a superficial analysis of carbon emissions, and it is difficult to measure the actual effect of changes in carbon emissions caused by government efforts to save energy and reduce emissions. Therefore, this paper constructs a model of the carbon emission decoupling efforts of Xi'an based on GDIM. Decoupling efforts refer to all policies or measures in socio-economic development that directly or indirectly lead to a reduction in total carbon emissions. Based on the GDIM decomposition results, if the change in carbon emissions is expressed as ΔC , which is ΔZ in equation (32), the government's decoupling efforts can be further evaluated by excluding the change in carbon emissions due to economic growth factors from the change in total carbon emissions. The value of the government's emission reduction effort ΔC_F from the base year to period t can be expressed indirectly as:

$$\Delta C_F = \Delta C - \Delta C_{X_1} = \sum_{i=2}^{10} \Delta C_{X_i}. \quad (35)$$

From equation (35), it can be seen that the output scale effect ΔC_{X_1} is negatively correlated with the government's effort to reduce emissions ΔC_F . Based on the GDIM decomposition model, a decoupling effort model can be constructed as:

$$D = \frac{\Delta C_F}{\Delta C_{X_1}} = \frac{\sum_{i=2}^{10} \Delta C_{X_i}}{\Delta C_{X_1}} = \sum_{i=2}^{10} D_{X_i}, \quad (36)$$

where, D is the total decoupling effort index of carbon emissions. If $D \leq 0$, it is the “no decoupling effort” state. If $0 < D < 1$, it is the “weak decoupling effort” state. If $D \geq 1$, it is the “strong decoupling effort” state. $D_{X_i} = \Delta C_{X_i} / \Delta C_{X_1}$, where D_{X_2} , D_{X_3} , D_{X_4} , D_{X_5} , D_{X_6} , D_{X_7} , D_{X_8} , D_{X_9} and $D_{X_{10}}$ denote the decoupling efforts of GDP (GDP), OCI (CO_2/GDP), EC (E), ECCI (CO_2/E), STII (T), STIICI (CO_2/T), population (P), CPC (CO_2/P), STIIE (GDP/T) and EI (E/GDP), respectively.

4 Results and Discussion

The data of economic and environmental indicators involved in this paper can be obtained from *Xi'an Social Statistics Yearbook*, *Shaanxi Social Statistics Yearbook*, *Shaanxi Science and Technology Statistics Yearbook*, and *China Energy Statistics Yearbook*.

4.1 Dynamic Analysis of Carbon Emissions

4.1.1 Carbon Emissions and Carbon Sequestration Capacity

Figure 1 shows the dynamic changes in Xi'an's carbon emissions between 1995 and 2021. Net carbon emissions increased from 899.12×10^4 tons in 1995 to 4146.96×10^4 tons in 2021, with an average annual growth rate of 6.06%. In terms of the five-year planning period¹ in China, the net carbon emissions grew fast during the 10th Five-Year Plan and grew relatively

¹Five-Year Plan time in China: the 9th Five-Year Plan (1996–2000), the 10th Five-Year Plan (2001–2005), the 11th Five-Year Plan (2006–2010), the 12th Five-Year Plan (2011–2015), the 13th Five-Year Plan (2016–2020), the 14th Five-Year Plan (2021–2025), the 15th Five-Year Plan (2026–2030), etc.

slowly during the 12th Five-Year Plan. In the 9th and 12th Five-Year Plan, the average value of net carbon emissions is higher than the initial and final values, showing an inverted “V” shaped trend. In the remaining periods, the average value is between the initial and final values, showing an upward trend. Total carbon emissions increased from 1384.99×10^4 tons in 1995 to 4881.73×10^4 tons in 2021, with an average annual growth rate of 4.96%. The analysis shows that with the accelerated pace of urbanization and industrialization in Xi'an, carbon emissions are increasing rapidly, posing certain challenges to achieving the “double carbon” goal.

The carbon sequestration capacity of Xi'an increased slowly relative to the carbon emissions, from 485.87×10^4 tons in 1995 to 734.77×10^4 tons in 2021, with an average annual growth rate of 1.60%. Over the period, the carbon sequestration capacity of forests contributed 86.40%~92.65%, with an average of 90.71%. During the 10th Five-Year Plan period, the carbon sequestration capacity grew faster due to the significant growth of forests, with an average annual growth rate of 5.41%. The slight decrease during the 11th Five-Year Plan was mainly due to the decrease in grassland and agricultural production, while the decrease during the 12th Five-Year Plan was mainly due to the decrease in the forest. The result shows that total carbon emissions were much higher than the carbon sequestration capacity in Xi'an, and the growth rate of total carbon emissions was also much higher than the carbon sequestration capacity. Therefore, Xi'an was in a carbon surplus.

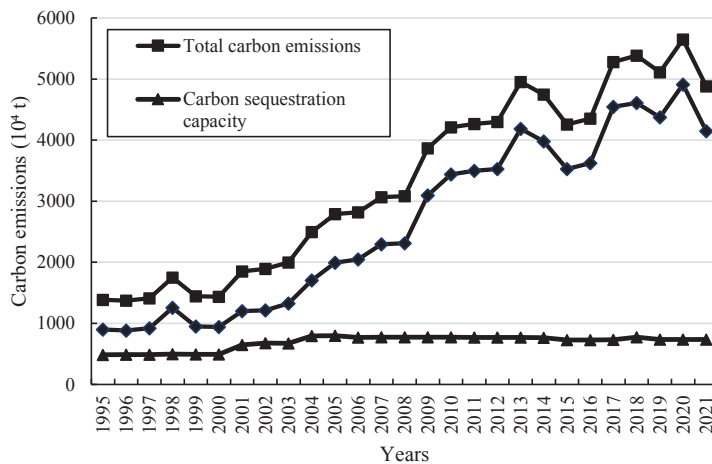
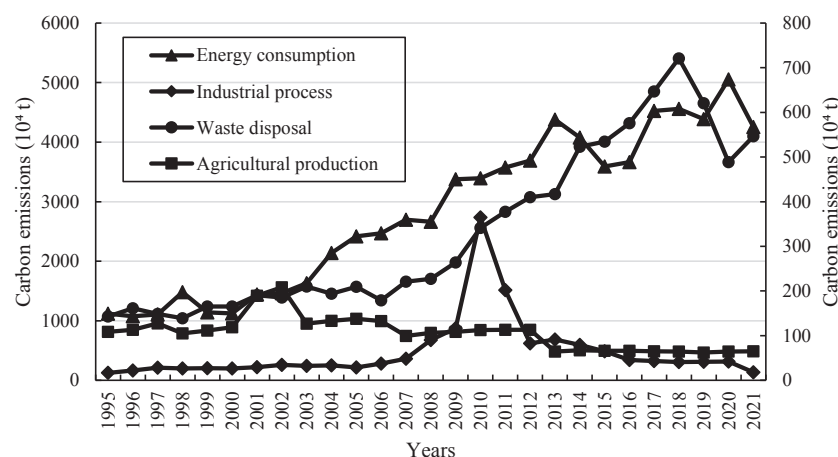


Figure 1 Carbon emission dynamics

4.1.2 Sector Carbon Emissions

Sector carbon emissions are shown in Figure 2. It shows a strong increase in the energy consumption sector and a decrease in the agricultural production sector. The share of carbon emissions in the energy consumption sector ranged from 77.38% to 89.46%, with an average of 83.83%, and was the largest share of the sector. Carbon emissions increased from 1117.24×10^4 tons in 1995 to 4252.15×10^4 tons in 2021, with an average annual growth rate of 5.28%. The carbon emission trend of the energy consumption sector was similar to the net carbon emission pattern of Xi'an, i.e., the carbon emission grew rapidly in the 10th Five-Year Plan period, and slowed down in the 12th Five-Year Plan period. It showed an inverted “V” shaped development



Note: The energy consumption sector corresponds to the left axis, and the industrial process, waste disposal, agricultural production sectors correspond to the right axis.

Figure 2 Carbon emission dynamics

in the 9th and 12th Five-Year Plan periods, and an upward trend in the rest of the periods. The main reason is that the energy structure of Xi'an is dominated by fossil energy sources, especially coal, which accounts for a relatively large share. In 2021, for example, the consumption of raw was 828.09×10^4 tons (327.12×10^4 tons in 1995), accounting for 58.50% of the total energy, which is 6.70% lower than in 2020. Therefore, in terms of energy structure, the key to achieving the “double carbon” goal is to reduce the reliance on fossil energy for Xi'an.

The share of carbon emissions from the industrial process sector ranged from 0.37% to 8.66%, with an average value of 1.89%. The industrial process sector increased from 16.55×10^4 tons in 1995 to 18.15×10^4 tons in 2021, with an average annual growth rate of 0.36%. During the period from the 9th to 11th Five-Year Plan, the carbon emissions of the industrial process sector increased fast, especially during the 11th Five-Year Plan with an average annual growth rate of 76.77%. The main reason was the rapid urbanization of Xi'an, which led to the expansion of the urban area and an increase in the demand for cement. In particular, the release of the Xi'an City Master Plan (2008–2020) accelerated the process of urbanization in Xi'an. In the 12th and 13th Five-Year Plan periods, the rapid growth trend was reversed and later showed a declining trend.

The share of carbon emissions in the waste disposal sector ranged from 6.35% to 13.39%, with an average value of 9.87%. The waste disposal sector increased from 142.96×10^4 tons in 1995 to 546.53×10^4 tons in 2021, with an average annual growth rate of 5.29%. During the 9th Five-Year Plan period, the average value was lower than the initial and final values, showing a “V” shaped trend. Carbon emissions increased rapidly between the 9th and 12th Five-Year Plan, it was related to the accelerated pace of urbanization during the period. However, in the 13th Five-Year Plan period, the average annual growth rate was negative, and the trend was decreasing from 2018 to 2021, indicating that the carbon growth trend was effectively controlled. In 2020, the *Law of the People's Republic of China on the Prevention and Control of Environmental Pollution by Solid Waste* and the *Regulations on the Prevention and Control*

of *Environmental Pollution by Solid Waste in Shaanxi Province* were introduced to increase the efforts in solid waste disposal.

The share of the agricultural production sector ranged from 1.14% to 11.00%, with an average value of 4.41%. The agricultural production sector decreased from 108.23×10^4 tons in 1995 to 64.90×10^4 tons in 2021, with an average annual decrease of -1.95% . It was the only sector to show a declining trend in carbon emissions. From 1995–2002, carbon emissions were on an upward trend and had been on a downward trend since then. On the one hand, agricultural production activities decreased as urbanization increased. On the other hand, the level of agricultural technology in Xi'an had increased over the past years, which helped to reduce carbon emissions.

4.1.3 Carbon Emissions of Energy Consumption Sector

According to the mentioned above, the largest carbon-emitting sector is energy consumption in Xi'an. Therefore, it is necessary to analyze the carbon emission characteristics of this sector. The share of carbon emissions in the sector is shown in Figure 3, and carbon emissions are shown in Figure 4. The share of industrial production ranged from 37.69% to 77.80%, with an

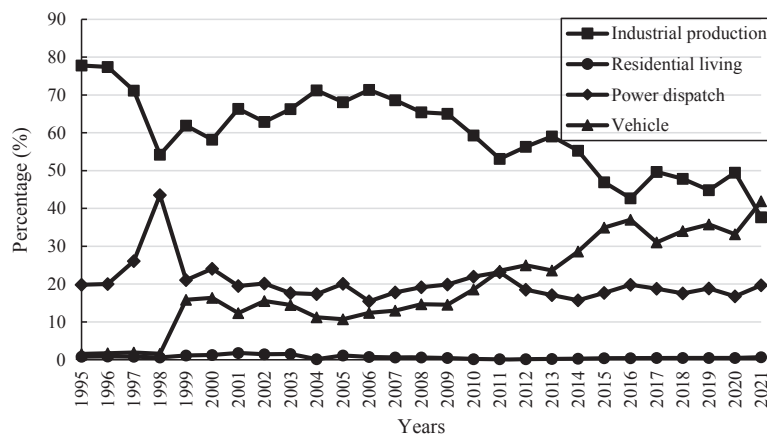


Figure 3 The share of carbon emissions in the energy consumption sector

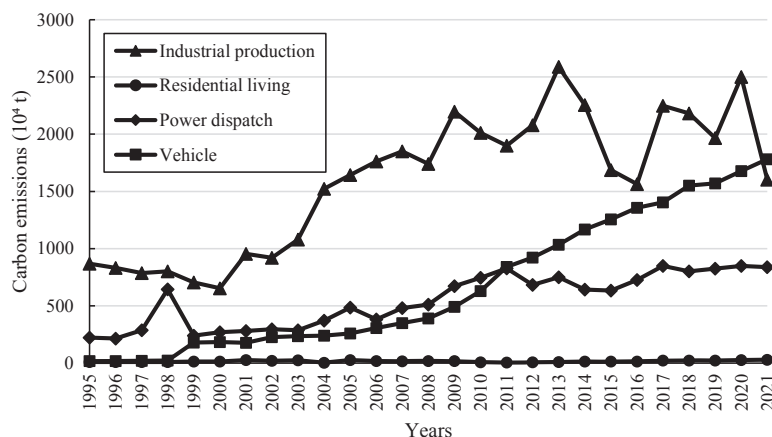


Figure 4 Carbon emissions in the energy consumption sector

average value of 59.57%. The proportion took a downward trend; however, it was still the largest share of the energy consumption sector. Carbon emissions from industrial production increased from 869.23×10^4 tons in 1995 to 1602.62×10^4 tons in 2021, with an average annual growth rate of 2.38%. The absolute volume was the highest in the energy consumption sector. During the 9th Five-Year Plan period, carbon emissions of industrial production showed a decreasing trend; during the 10th, 11th, and 13th Five-Year Plan periods, those increased rapidly; during the 12th Five-Year Plan period, those showed an inverted “V” shaped development trend.

The share of residential living ranged from 0.16% to 1.81%, with a mean value of 0.69%. Emissions increased from 8.75×10^4 tons in 1995 to 29.96×10^4 tons in 2021, with an average annual growth rate of 4.85%. The absolute volume was the lowest in the energy consumption sector. Residential living emissions were growing faster as Xi'an's population increased. Therefore, compared with other factors, the natural growth of the population has a limited impact on carbon emissions.

The share of power dispatch ranged from 15.46% to 43.57%, with an average value of 20.28%. Emissions increased from 221.93×10^4 tons in 1995 to 837.67×10^4 tons in 2021, with an average annual growth rate of 5.24%. During the 12th Five-Year Plan period, carbon emissions of power dispatch decreased slightly, while the rest of the planning periods showed an obvious growth trend.

The share of vehicle emissions ranged from 1.55% to 41.91%, with an average value of 19.46%. It was also the fastest-growing sector in terms of the share of energy consumption. Emissions increased from 17.33×10^4 tons in 1995 to 1781.90×10^4 tons in 2021, with an average annual growth rate of 19.51%. During the 9th Five-Year Plan period, the average annual growth rate even reached as high as 78.34%. The vehicles in Xi'an increased from 9.70×10^4 in 1995 to 445.38×10^4 in 2021. Therefore, promoting new energy vehicles in Xi'an is of great significance for reducing carbon emissions.

4.2 Results of Decoupling and Decoupling Effort

4.2.1 The Decoupling Results

This paper measured the carbon emissions of Xi'an from 1995 to 2021. Huang and Tian^[52] simulated carbon emissions from 2022 to 2060 based on Monte Carlo simulation and scenario simulation methods. The results show that the “double carbon” goal was achievable under the technology breakthrough scenario. Based on the Tapio decoupling model, the decoupling of economic development from carbon emissions at different stages during the period 1995–2060 is shown in Appendix Table A1. From the 9th to the 14th Five-Year Plan, only the 10th Five-Year Plan was in the state of “expansive coupling”, while the rest of the periods were in the state of “weak decoupling”. It showed that the growth rate of carbon emissions in Xi'an during the 10th Five-Year Plan was close to the economic growth rate, which was a rough growth at the expense of the ecological environment. During the 12th Five-Year Plan period, the decoupling index value was 0.02, indicating that Xi'an had put the concept of green development into practice. In the 13th Five-Year Plan period, the index value recovered and has been declining ever since. After the 15th Five-Year Plan (more precisely, after the carbon peak), carbon emissions become strongly decoupled from economic development. The decoupling index value

is decreasing, indicating an increasing intensity of decoupling, i.e., both achieving the goal of economic growth and a gradual reduction in carbon emissions.

According to the carbon emission sub-accounts, the energy consumption sector showed an “expansive coupling” state during the 10th Five-Year Plan period and a “weak decoupling” state for the rest of the periods. The energy consumption account shows a high degree of consistency with the evolution of the index state to the overall account over the analysis period. It indicates that this account has an important influence on the decoupling or not of economic development from carbon emissions. This is because the energy consumption sector accounts for the largest share of carbon emissions in Xi’an.

The industrial process sector was in a state of “weak decoupling” during the 9th Five-Year Plan, an “expansive negative decoupling” state during the 11th Five-Year Plan, and a “strong decoupling” state for the rest of the periods. During the 11th Five-Year Plan period, Xi’an experienced the most rapid urbanization and urban expansion, resulting in a rapid increase in demand for cement and its raw materials.

The decoupling index of the waste disposal sector shows a reverse “U” trend, with the highest value (0.82) achieved during the 11th Five-Year Plan period, indicating an “expansive coupling” state where carbon emissions from waste management grew rapidly alongside economic growth. This is closely related to the accelerated urbanization process in Xi’an during that period, and the related supporting facilities for waste management still need further improvement. During the 13th Five-Year Plan period, the waste disposal sector intensified the disposal of urban and industrial solid waste in accordance with the *Solid Waste Pollution Prevention and Control Law*, and revised the *Regulations on Urban Sewage Treatment and Reuse in Xi’an* to strengthen the management of urban sewage treatment and reuse, achieving a “strong decoupling” state.

The agricultural production account of all the accounts was the first to achieve a “strong decoupling” state, with only the 9th Five-Year Plan period showing a “weak decoupling” state during the analysis period. For the rest of the period, it remained in a “strong decoupling” state. However, looking at the decoupling index of this account, the index rebounded quickly to -0.04 during the 13th Five-Year Plan period, and there is a need to prevent it from entering the “weak decoupling” range.

4.2.2 The Decoupling Effort Results

The decoupling effort effects for each influencing factor are shown in Appendix Table A2. From 1996 to 2021, the decoupling effort value of Xi’an was -416.48×10^4 tons, and the decoupling effort index was 0.09, which was in the state of “weak decoupling effort”. It indicates that the government of Xi’an had made decoupling efforts but they were still insufficient. The decoupling effort contribution of STIIE (GDP/T) was the maximum at 0.73, while the decoupling effort contribution of STIICI (CO_2/T) was the minimum at -0.31 . During the analysis period, technological innovation played a crucial role in the carbon reduction of Xi’an, and was a key factor in achieving the “double carbon” goal.

The efforts made by the Xi’an government to reduce carbon emissions showed fluctuating characteristics. During the 9th and the 10th Five-Year Plan periods, the value of decoupling efforts in Xi’an was -57.78×10^4 and -395.51×10^4 tons, and the decoupling effort index was

positive, at 0.51 and 0.93 respectively, both in the “weak decoupling effort” state. The carbon intensity of STIICI (CO_2/T) had the maximum decoupling effort of 1.66 and 1.64, while the scale of STII (T) had the minimum decoupling effort of -2.16 and -2.09 , respectively. During the 10th, 11th, and 13th Five-Year Plan periods, the decoupling effort index of Xi'an was -2.39 , -1.71 , and -1.19 , respectively, which were in the state of “no decoupling effort”. This indicates that the government's efforts to reduce carbon emissions over the above periods had been insufficient compared to economic development. During the 10th Five-Year Plan period, the decoupling effort of OCI (CO_2/GDP) was maximum at 0.09, while the CPC (CO_2/P) was the minimum at -0.74 . During the 11th Five-Year Plan period, the decoupling effort of the STIICI (CO_2/T) was maximum at 0.67, while the STII (T) was minimum at -1.30 . During the 13th Five-Year Plan period, the decoupling effort of STIIE (GDP/T) was maximum at 0.45, while the decoupling effort of STIICI (CO_2/T) was minimum at -1.02 . The above analysis indicates that the most significant influencing factor in Xi'an decoupling efforts has changed. To achieve a higher level of decoupling, it is essential to give high importance to the critical role played by STIICI (CO_2/T) and STIIE (GDP/T).

To achieve the “double carbon” goal, the government of Xi'an needs to make further efforts to reduce carbon emissions. Based on the analysis of the decoupling effort index, it is necessary to improve from -1.19 during the 13th Five-Year Plan period to -1.12 during the 14th Five-Year Plan period. Although it is still in the “no decoupling effort” state, the main reason is that the effectiveness of various carbon reduction measures has a certain lag. During the 15th Five-Year Plan period, the decoupling effort index needs to reach the “strong decoupling effort” state of 1.76, so as to achieve the “carbon peak” goal in 2028–2029. To achieve the “carbon neutrality” goal, the decoupling effort index needs to reach the “strong decoupling effort” state of 1.75 and 4.35 respectively in the periods of 2041–2050 and 2051–2060.

Based on the analysis of the factors influencing decoupling effort, the maximum decoupling effort of EC (E) is 0.41 during the 14th Five-Year Plan period. To achieve the “carbon peak” goal during the 15th Five-Year Plan period and the “carbon neutrality” goal before 2060, the STIICI (CO_2/T) is the most important factor. Therefore, to achieve the “carbon peak” goal, Xi'an must rely on technological innovation to further reduce its dependence on fossil fuels during the 14th Five-Year Plan period. To achieve the “carbon neutrality” goal, it is necessary to significantly increase the decoupling effort of factors such as STIICI (CO_2/T).

5 Conclusions

According to IPCC 2019 and *Guidelines for the Preparation of Provincial Carbon Emission Peaking Action Plans*, the carbon emissions of Xi'an were measured in the energy consumption sector, industrial process sector, waste disposal sector, agricultural production sector, forestry and other land use sector in this paper. The decoupling effect of carbon emissions and economic development in Xi'an was analyzed by Tapio decoupling model. The decoupling effort model was constructed based on GDIM, and the decoupling effort of each influencing factor was analyzed according to the model. The results are as follows:

Firstly, during the period 1995–2021, both the carbon emissions and the net carbon emissions of Xi'an increased rapidly. Carbon emissions increased from 1384.99×10^4 tons in 1995 to

4881.73×10^4 tons in 2021, with an average annual growth rate of 4.96%. The carbon sequestration capacity increased from 485.87×10^4 tons to 734.77×10^4 tons, with an average annual growth rate of 1.60%. Net carbon emissions increased from 899.12×10^4 tons to 4146.96×10^4 tons, with an average annual growth rate of 6.06%.

Secondly, the energy consumption sector accounted for the largest share of carbon emissions, and it was the fastest-growing sector. The share of carbon emissions in the energy consumption sector ranged from 77.38% to 89.46%, with an average value of 83.83%. Carbon emissions increased from 1117.24×10^4 tons in 1995 to 4252.15×10^4 tons in 2021, with an average annual growth rate of 5.28%. The share of carbon emissions in the industrial process sector ranged from 0.37% to 8.66%, with an average value of 1.89% and an average annual growth rate of 0.36%. The share of carbon emissions in the waste disposal sector ranged from 6.35% to 13.39%, with an average value of 9.87% and an average annual growth rate of 5.29%. The agricultural production sector accounted for 1.14%~11.00%, with an average value of 4.41% and an average annual decrease of 1.95%, and it was the only sector with a decreasing trend.

Thirdly, in the energy consumption sector, industrial production had the largest share, increasing from 869.23×10^4 tons in 1995 to 1602.62×10^4 tons in 2021, with an average annual growth rate of 2.38%. Residential living had the lowest share, increasing from 8.75×10^4 tons in 1995 to 29.96×10^4 tons in 2021, with an average annual growth rate of 4.85%. Power dispatch increased from 221.93×10^4 tons in 1995 to 837.67×10^4 tons in 2021, with an average annual growth rate of 5.24%. Vehicle emissions increased from 17.33×10^4 tons in 1995 to 1781.90×10^4 tons in 2021, with an average annual growth rate of 19.51%, and it was the fastest-growing domain in the energy consumption sector.

Fourthly, according to the Tapio decoupling model, the 10th of the 9th to 14th Five-Year Plan period was in the state of “expansionary coupling”, while the rest of the period was in the state of “weak decoupling”. It shows that during the 10th Five-Year Plan period Xi’an adopted a sloppy growth method at the expense of the ecological environment. After the 15th Five-Year Plan (more precisely, after the carbon peak), carbon emissions become strongly decoupled from economic development. The goal of economic growth will be achieved while gradually reducing carbon emissions. The agricultural production sector was the first of all sectors to reach the state of “strong decoupling”.

Finally, the Xi’an government made efforts to decouple in the past, but these were not enough. The decoupling effort value was -416.48×10^4 tons, and the decoupling effort index was 0.09, which was in the state of “weak decoupling effort”. The maximum contribution of decoupling effort was 0.73 for the STIE (GDP/T). To achieve the “double carbon” goal, Xi’an must make further efforts to reduce carbon emissions. It is necessary to improve from -1.19 during the 13th Five-Year Plan period to -1.12 during the 14th Five-Year Plan period. During the 15th Five-Year Plan period, the decoupling effort index must reach the “strong decoupling effort” state of 1.76, and during the 2041–2050 and 2051–2060 periods, it must reach the “strong decoupling effort” state of 1.75 and 4.35, respectively.

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Table A2 Decoupling effort effect of each influencing factor in Xi'an

Years	Decoupling effort value (10^4t)	Decoupling Effort Index	E	T	P	CO_2/GDP	CO_2/E	CO_2/T	CO_2/P	GDP/T	E/GDP
1996-2000	-57.78	0.51	-1.32	-2.16	-0.13	0.97	1.13	1.66	-0.03	0.37	0.01
2001-2005	557.50	-2.39	-0.55	-0.62	-0.11	0.09	-0.30	-0.21	-0.74	0.02	0.03
2006-2010	878.48	-1.71	-0.47	-1.30	-0.06	0.29	-0.30	0.67	-0.71	0.08	0.08
2011-2015	-395.51	0.93	-0.25	-2.09	-0.07	0.95	0.27	1.64	0.05	0.32	0.12
2016-2020	700.49	-1.19	-0.28	0.24	-0.30	0.21	-0.26	-1.02	-0.24	0.45	0.02
1996-2020	-416.48	0.09	-0.14	-0.03	-0.05	0.04	0.01	-0.31	-0.16	0.73	0.00
2021-2025	349.88	-1.12	0.41	-0.47	-0.05	-0.57	0.06	-0.28	-0.25	0.02	0.02
2026-2030	-329.66	1.07	-0.39	-1.05	-0.16	0.97	0.44	1.04	0.18	0.00	0.04
2031-2040	-969.78	1.76	-0.30	-1.03	0.04	1.08	0.55	1.15	0.17	0.00	0.09
2041-2050	-1644.64	1.75	-0.07	-0.39	0.04	0.80	0.30	0.66	0.18	0.09	0.15
2051-2060	-1075.85	4.35	0.08	-1.09	0.14	1.68	0.84	1.79	0.75	0.01	0.16
2021-2060	-2965.80	2.75	-0.46	-0.88	-0.04	1.05	1.10	1.05	0.76	0.00	0.16