

China's fast growing CO₂ emissions driven by increasing consumption in 1992-2012: A structural decomposition analysis

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Abstract. China is the largest carbon emitter worldwide and subsequently the greatest contributor to increments in global carbon emissions. Uncovering the driving forces behind China's rapid CO₂ emission growth can provide a theoretical basis for formulating scientific emission reduction policies, which are of great significance for mitigating global climate change. Based on an updated noncompetitive input-output model and structural decomposition analysis, the driving factors and their mechanisms of action for the rapid growth of China's carbon emissions from 1992 to 2012 were explored in this study, with greater attention to the period 2007-2012. The main conclusions are as follows. (1) China's carbon emissions increased by 7424.2 MtCO₂ from 1992 to 2012. Particularly rapid growth of carbon emissions occurred during the periods 2002-2007 and 2007-2012, which respectively accounted for 43.33 % and 36.94% of the accumulated emission increments. (2) From 2007 to 2012, the growth of China's carbon emissions was almost entirely driven by the expansion of the final demand scale, whereas the decline in carbon intensity dominantly mitigated carbon emissions. The effects of input-output structure and final demand structure also contributed to abating carbon emissions, with the relatively small contributions.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) declared that the rapid growth of anthropogenic greenhouse gas (GHG) emissions was quite likely the main cause of the current change in climate [1]. Reducing anthropogenic GHG emissions, therefore, is crucial for mitigating climate change. China is one of the most important carbon emitters worldwide. During the period 1992-2012, the share of China's carbon emissions in total global emissions increased from 12.0% to 27.5% [2], making China the world's largest carbon emitter. Reduction in China's carbon emissions is vital for mitigating global climate change.

To fight actively against climate change, the Chinese government has proposed several carbon emission reduction targets. In 2009, China announced its plan to cut CO₂ emissions per unit of GDP (carbon intensity) by 40%-45% by 2020 compared to the 2005 level. In 2014, China introduced a plan to reach its national carbon emission peak around 2030 in the "Sino-US Joint Statement on Climate Change." In 2015, China further committed to cut its carbon intensity by 60%-65% compared to the 2005 level in the "Sino-US Heads Joint Statement on Climate Change." In this context, it is of critical



importance to uncover the main driving forces of China's carbon emission growth and accordingly formulate a targeted carbon emission reduction program.

With China's steadfast determination to mitigate carbon emissions, a growing number of researchers have applied structural decomposition analysis (SDA) to explore the driving factors of China's energy consumption and carbon emissions in recent years. According to research focus, the current literature generally can be classified into three categories. The first category encompasses the driving factors of China's national energy intensity or carbon intensity changes [3-7]. The second category focuses on the influential factors driving up energy consumption and carbon emissions of China's industrial sectors [8-17]. The third category of research varies slightly in that it regards the rapid growth of carbon emissions from residents' consumption and their driving factors in China [18-19]. However, it should be noted that the current literature is subject to certain defects, including: (1) most of the studies used the default emission factors published by the IPCC to conduct carbon emission accounting, which might lead to significant overestimation of China's carbon emissions [20]; (2) the overall impacts of driving factors were carefully examined whereas their impacts at the sectoral level rarely received attention; and (3) most of the studies depended on the Input-Output Tables of China 2007, the time lag of which cannot reflect the latest dynamics of the Chinese economic and production systems.

In this context, SDA was applied in this study to thoroughly and comprehensively investigate the drivers of and their impacts on China's carbon emissions growth. Firstly, to estimate carbon emissions more accurately, the latest carbon emission coefficients of fossil fuels at the subsectoral level of China and the revised data of energy consumption were used. Secondly, SDA secondary decomposition was introduced to reveal further the sectoral-level impacts of related driving factors on carbon emissions. Finally, based on the newly released Input-Output Tables of China 2012, the driving forces of and their mechanisms of action on China's carbon emission growth from 2007 to 2012 were explored.

2. Method and data

2.1. Environmentally extended input-output model

The environmentally extended input-output model (EEIOM) was first proposed by Leontief [21]. By incorporating the coefficients of pollutant emissions into the traditional input-output model, the EEIOM can capture the impacts of final demand and input-output structure on regional or national pollutant emissions. The structure of the EEIOM used in this study is:

$$c = Fx = F(I - A)^{-1}y, \quad (1)$$

where c refers to the amount of carbon emissions from all economic sectors; and F is a $(1 \times n)$ row vector of sectoral carbon intensity; x is a $(n \times 1)$ column vector of sectoral gross output; and y is a $(n \times 1)$ column vector of sectoral final demand; in all of which n denotes the number of economic sectors in China. Both I and A are $(n \times n)$ matrices; the former represents a unit matrix whereas the latter indicates a matrix of total production coefficients. $(I - A)^{-1}$ is the total Leontief inverse matrix, the elements of which represent the complete consumption of the other sectors' products caused by increasing unit final demand of one specific sector.

2.2. Structural decomposition analysis

SDA has the potential to detect both direct and indirect impacts of related driving factors on the changes in the investigated indicators [22]. This method has two kinds of decomposition form. Additive decomposition is usually applied to analyze absolute indicators; the change in an absolute indicator is expressed as the sum of the effects of related factors. Multiplicative decomposition is widely used on relative indicators; the change in a relative indicator is denoted as the product of the effects of related factors [3]. To uncover the driving forces of China's carbon emissions, the form of additive decomposition was adopted in this study. We let L represent $(I - A)^{-1}$ in equation (1) and

expressed y as the product of the final demand structure (y_s) and final demand volume (y_v), thus the change in carbon emissions (Δc) within a specific interval was expressed as [12–17]:

$$\Delta c = \Delta FLy_s y_v + F \Delta Ly_s y_v + FL \Delta y_s y_v + FLy_s \Delta y_v, \quad (2)$$

where y_s is the shares of sectoral final demand in the national aggregate final demand; the first term on the right side of the equation indicates carbon emission change caused by aggregated changes in the emission intensities; the second term represents the changes in the input-output structure; the third term denotes the changes in the final demand structure; and the fourth term indicates the changes in the final demand volume. In general, there are $n!$ forms of equivalent decompositions with n independent variables in the model [23]. In this study, all $n!$ forms were averaged using the method proposed by Li [24].

2.3. Data

We calculated CO₂ emissions from energy activities and industrial processes as Peters et al. [25] did. The data of energy consumption and industrial products produced are derived from various statistical yearbooks, including the *China Energy Statistical Yearbook* and the *China Industrial Economy Statistical Yearbook*. As the National Bureau of Statistics of China has revised China's energy data for 1996 to 2012 [26–27], the latest revision of data was used.

We followed the procedures in Liu and Peng [28] to construct China's input-output tables with 35 sectors at 2000 prices in 1992, 1997, 2002, 2007, and 2012. Many studies assume the emission intensities of imported products are the same as those of domestic products, which may lead to overestimation of the carbon emissions induced by final demand [29]. To avoid this problem, we converted the tables to noncompetitive tables using the method in Weber et al. [30], which subtracts imported products from intermediate demand and final demand proportionally. The 35 sectors of input-output tables are shown in Table 1.

Table 1. Sector classification used in the study

No.	Sector	No.	Sector
1	Agriculture	18	Transportation machinery and equipment manufacturing
2	Coal mining and dressing	19	Electric machinery and equipment manufacturing
3	Petroleum and natural gas extraction	20	Electronic and communication equipment manufacturing
4	Metals mining and dressing	21	Instruments, meters, and other measuring equipment manufacturing
5	Nonmetal minerals mining and dressing	22	Other manufacturing products
6	Other ores mining and support activities for mining	23	Utilization of wastes
7	Food, beverage, and tobacco processing	24	Repair service for metal products, machinery and equipment
8	Textile industry	25	Electricity and steam production and supply
9	Garments, leather, down, and other fiber products	26	Gas production and supply
10	Timber processing and furniture manufacturing	27	Water production and supply
11	Papermaking, printing, and cultural, educational articles	28	Construction

No.	Sector	No.	Sector
12	Petroleum processing, coking, and nuclear fuel processing	29	Transportation and warehousing
13	Chemical industry	30	Post and Telecommunications
14	Nonmetal mineral products	31	Wholesale and retail trade
15	Smelting and pressing of metals	32	Hotel and restaurants
16	Metal products	33	Finance and insurance
17	Industrial machinery and equipment manufacturing	34	Real estate
		35	Other services

3. Results and discussion

3.1. Primary decomposition of factor contributions to national carbon emissions

As seen in figure 1, the factor of carbon intensity made the largest contribution to mitigating the growth of China's carbon emissions, whereas the factor of final demand dominantly drove emissions up from 1992 to 2012. However, the contributions of driving factors exhibited different characteristics across the periods.

From 1992 to 2002, the amount of China's carbon emissions increased by 1465.1 MtCO₂, accounting for 19.7% of the 1992-2012 accumulated emission increments. The growth of China's carbon emissions was a race between booming consumption and improving efficiency within this period [17], in which the positive impacts of final demand were even stronger than the negative impacts of carbon intensity. During the period 2002-2007, the growth of China's carbon emissions accelerated with an absolute increment of 3217.0 MtCO₂. The input-output structure was another key factor driving up China's carbon emissions [12]. Emission increments caused by the input-output structure factor were almost 75% of those caused by the final demand factor, which implied that China had experienced extensive development, as featured by the heavy energy consumption and carbon emissions during the period. From 2007 to 2012, China's carbon emissions increased by 2742.1 MtCO₂, which were almost entirely contributed by the expansion of final demand. All of the carbon intensity, input-output structure, and final demand structure factors contributed to offsetting carbon emissions, the aggregate effects of which reduced emissions by 817.9 MtCO₂. The factor of carbon intensity still had the greatest effects on mitigating carbon emissions, but its contributions were just 22.0% of those during the period 2002-2007.

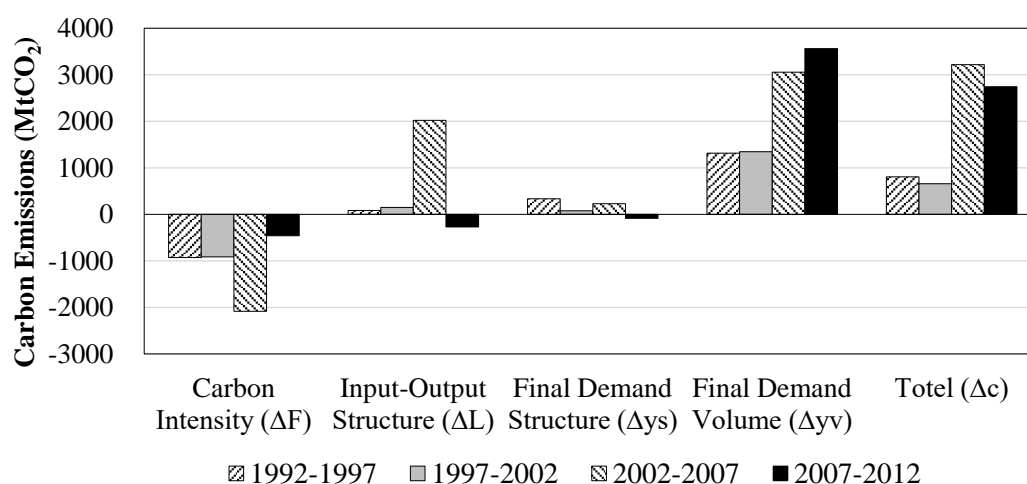


Figure 1. Changes in industrial CO₂ emissions of China via emission determinants for 1992-2012

3.2. Carbon intensity effects

Although still the largest contributor to slowing down the growth of carbon emissions, the effect of carbon intensity factor significantly declined during the 2007-2012 period compared with that during the three other periods. As seen in figure 2, carbon intensities declined in the majority of sectors and hence contributed to offsetting national carbon emissions. The sectors of nonmetal mineral products (sector 14); chemical industry (sector 13); transportation and warehousing (sector 29); as well as food, beverage, and tobacco processing (sector 7) were the four biggest contributors to the effects of carbon intensity on offsetting emissions, with individual contributions of 65.42%, 37.82%, 17.77%, and 11.87%, respectively, to the total carbon intensity effects, resulting in an integrated contribution of 132.87%.

However, it should be noted that carbon intensity of the electricity and steam production and supply sector (sector 25) showed an upward trend in the same period, which was the main reason for the weakened aggregate-inhibiting effects of the carbon intensity factor. More specifically, the carbon intensity of this sector increased by 0.66 tCO₂/10⁴RMB, which caused the 425.5 MtCO₂ of emission increments and negatively contributed (-92.59%) to the total carbon intensity effects. The main reason for this was that China was at a critical period of rapid urbanization and industrialization during 2007 to 2012, with booming demand for electricity. The “rich coal, lack of oil, and less gas” energy resource endowment of China determined that the increased supply of electricity were mainly generated from coal, which eventually led to the rise of carbon intensity in the electric and heat power sector. Judging from this, optimization of the electricity structure and enhancement of the low-carbon power generation mode would have great potential for reducing carbon intensity and carbon emissions in this sector.

The dynamics of China’s carbon intensity can be further analyzed by the changes in energy intensity and energy structure. From 2007 to 2012, although China’s energy consumption was still coal based, the proportion of coal consumption in the total energy consumption decreased to 68.5% in 2012. In addition, for the Eleventh Five-Year Plan period, the Chinese government invested heavily in clean energy, renewable energy, and other non-fossil energy technologies, causing rapid development of clean energy (including hydropower installed capacity with an average annual growth rate of 12.9% to the Eleventh Five Planning End), which reached 220 million kilowatts, ranking first in the world. Meanwhile, the 2010 nuclear power installed capacity reached 10.82 million kilowatts, and wind power was growing annually by an average of 89.8%. The reduction in China’s carbon emission intensity was mainly due to an increase in the proportion of clean energy use and decreased energy consumption per unit GDP.

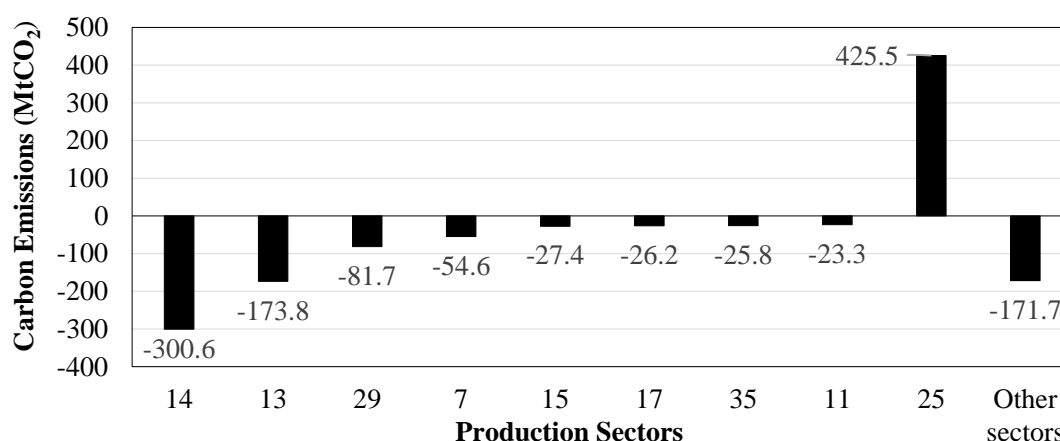


Figure 2. CO₂ emission changes caused by sectoral emission intensity changes for 2007-2012

3.3. Final demand volume effects

As seen in figure 3, fixed capital formation leads to the largest increment of total carbon emissions, followed by exports and urban residents' consumption. These accounted for approximately 90% of the

emissions from the final demand volume effects. The construction sector (sector 28) accounted for about 25% of the emission increase. This conclusion is consistent with those of Peters et al. [17] and Minx et al. [12]. The main reason for this is the vigorous promotion of China's urbanization from 1992 to 2012, with construction products existing in the form of fixed capital formation. The construction sector required large amounts of carbon-intensive products, such as electric power, steel, and cement, thus indirectly stimulating the rapid growth of carbon emissions.

The emission increment induced by exports accounted for 26.14% of the total effect of final demand volume change in the period 2007-2012. Export product distribution is more dispersed, wherein the electronic and communication equipment manufacturing industry (sector 20) had the largest share of 2.37%, followed by the industrial machinery and equipment manufacturing industry (sector 17), accounting for 1.92%. China, as the "world's factory", produced abundant carbon-intensive goods for the world, such as electronics, communication equipment, steels and others. These products greatly increased China's carbon emissions.

The increase in carbon emissions stimulated by urban residents' consumption accounted for 16.94% of the effect of final demand volume change for 2007-2012. This is mainly because the State Council vigorously promote urbanization, including encouraging the rural labor to work in cities and towns. The Eleventh Five-Year Plan included a proposal for the urbanization rate increase to 47% and a target to increase the urban labor force to 45 million. This initiative promoted an increase in urban population and an increase in urban incomes. Lifestyles became more energy consumptive with subsequent increased carbon emissions, and therefore the changes in consumption behavior of urban residents sped up the rate of carbon emissions. The increase in urban consumption was mainly in sectors closely related to daily living, such as other services (sector 35); food, beverage and tobacco processing (sector 7); and real estate (sector 34).

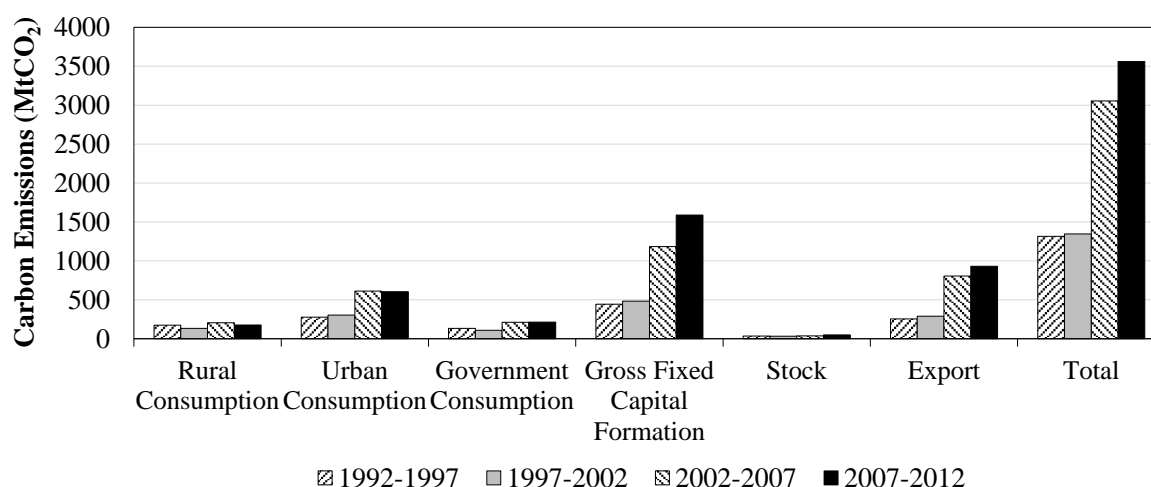


Figure 3. CO₂ emission changes caused by final demand volume change for 1992-2012

3.4. Input-output structure effects and final demand structure effects

The factor of input-output structure represents the generalized technological advances, including science and technology, management system, and industrial structure change. The effect of the input-output structure factor on carbon emission growth was positive from 1992 to 2012, but negative (-271.8 MtCO₂) during the subperiod 2007-2012. This implies that the economic development of China changed from "extensive" mode to "intensive" mode, which placed more emphasis on low carbon production. From 2007 to 2012, the nonmetal mineral products industry (sector 14) caused the most carbon emissions (59.8 MtCO₂), followed by the smelting and pressing of metals industry (sector 15, 52.1 MtCO₂); the transportation and warehousing industry (sector 29, 48.3 MtCO₂); and agriculture sector (sector 1, 39.6 MtCO₂). These sectors are mainly in the primary and secondary industries, which need to invest a lot of energy and resources for production.

The effects of the final demand factor have shifted from driving up emissions during the period 1992-2007 to offsetting emissions for 2007-2012. It was demonstrated that the structure of final demand in China has been gradually turning from high-carbon products to low-carbon products in recent years. The effects in various sectors of final demand structure on carbon emissions are quite different from 2007 to 2012. Among them, the smelting and pressing of metals industry (sector 15) had the largest reduction (-190.7 MtCO₂), accounting for 220.43% of the total final demand structure factor reductions, followed by the sectors of electricity and steam production and supply (sector 25, -145.0 MtCO₂) and textiles (sector 8, -79.62 MtCO₂). These sectors accounted for the gradual decreasing proportion of final demand, reduced carbon emissions. Meanwhile, sectors causing increased carbon emissions were mainly construction (sector 28, 298.2 MtCO₂), transportation machinery and equipment manufacturing (sector 18, 147.7 MtCO₂), and industrial machinery and equipment manufacturing (sector 17, 101.0 MtCO₂). These sectors made increasing contributions to the final demand effects and hence led to the growth of carbon emissions.

4. Conclusions

The carbon emissions of China increased by 7424.2 MtCO₂ during the period 1992-2012, to which carbon intensity and final demand volume were the largest negative and positive contributors, respectively. The rapid growth of carbon emissions was witnessed during the subperiods 2002-2007 and 2007-2012, which accounted for 43.33% and 36.94%, respectively, of the 1992-2012 emission increment. More importantly, it should be noted that the growth of China's carbon emissions was almost entirely driven by the expansion of the final demand scale for 2007-2012, with an absolute contribution of 3560.0 MtCO₂. All of the carbon intensity, input-output structure, and final demand structure factors contributed to mitigating carbon emissions, but their combined inhibitory effects were just 22.97% of the simulative effects of final demand volume. Based on these facts, final demand volume is proposed as the key factor in abating China's carbon emissions at the current stage.

The factor of carbon intensity played the dominant role in mitigating the growth of China's carbon emissions during the period 1992-2012. The inhibitory effects of carbon intensity factor within 2007-2012 were only half of those within 1992-2002 and 22.04% of those within 2002-2007, which presented a significant downward trend across the subperiods. The growth of carbon intensity of the electricity and steam production and supply sector was the main reason for the weakened 2007-2012 inhibitory effects of the carbon intensity factor. In the same period, the sectors of nonmetal mineral products; chemical industry; transportation and warehousing; as well as food, beverage, and tobacco processing ranked as the four biggest sectoral contributors to the inhibitory effects of carbon intensity, with a combined contribution of 132.87% to the total carbon intensity effects.

The factor of final demand volume played an increasingly important role in driving up carbon emissions in China. The emission increments for 2007-2012 caused by the final demand volume factor were 16.56% larger than they were for 2002-2007, and 264% larger than they were for 1997-2002. Gross fixed capital formation, exports, and residents' consumption dominantly affected and thus drove up emissions, the combined effects of which accounted for 87.68% of the total effects of final demand volume. Furthermore, the emission increments driven by gross fixed capital formation mainly stemmed from the construction sector, whereas that driven by exports were mainly caused from the communications equipment, computers and other electronic equipment manufacturing sector.

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