RESEARCH ARTICLE

Whether China made efforts to decouple economic growth from CO$_2$ emissions?-Production vs consumption perspective

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Abstract

Decoupling analysis is able to reveal the linkage between economic growth and environmental pressure. However, traditional studies mostly concentrate on production-based decoupling analysis and ignore the pressure emerging from supply chains to satisfy the final consumption. Through a comprehensive framework integrating input–output analysis, decomposition methods, and the Tapio index, this work may be considered the first attempt to explore whether China made efforts to decouple economic growth from CO$_2$ emissions from production-based and consumption-based perspectives simultaneously. We found that (1) CO$_2$ emissions in China expanded by around 1.6-fold during 2002–2015, of which *Production and supply of electricity and heat* and *Construction* contributed most to the production-based emissions (PBE) and consumption-based emissions (CBE), respectively; (2) Three-quarters of sectors presented weak decoupling or strong decoupling under both PBE and CBE perspectives, and *Textile* was the only sector achieving strong decoupling under both perspectives; (3) All sectors have made efforts to decouple economic growth from CO$_2$ emissions under PBE perspective, while several sectors failed under CBE perspective. Overall, the decoupling status for PBE was better than that for CBE during the study period. Our results are able to provide targeted and effective references for allocating decoupling responsibilities between producers and final consumers more adequately and reasonably.

Keywords Production-based emissions · Consumption-based emissions · Decoupling effort Economic growth · Decomposition analysis · China

Highlights
- The decoupling status of PBE and CBE with economic growth are analyzed.
- *Electricity* and *Construction* contribute most to PBE and CBE, respectively.
- Change of economic structure, energy intensity, and emission intensity reduce CO$_2$ emissions.
- All sectors make efforts to reduce CO$_2$ emissions under production-based perspective.
- Some sectors fail to achieve decoupling progress under consumption-based perspective.

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Introduction

During the past decades, China has achieved remarkable economic growth accompanied by a large quantity of energy consumption and associated greenhouse gas emissions. In 2007, China overtook the USA as the largest CO_2 emitter and subsequently exceeded the sum of CO_2 from the USA and the EU several years later (Boden et al. 2017). The enormous environmental pressure urges China to develop in a green, low-carbon, and sustainable mode, which has to realize the coordination between economic benefits and environmental sustainability. Accordingly, China has announced new mitigation targets for 2030 to further reduce carbon intensity by 60–65% compared with the 2005 level and reach the peak of CO_2 emissions. Industrial sectors are the key economic motor in China, while they are also the dominant CO_2 emission source (Zhao et al. 2016; Gao et al. 2019a, b, c; Ma et al. 2019). The government has been attempting to develop differentiated mitigation strategies and carbon quotas for different sectors, which requires fairly clear pictures of sectoral CO_2 emissions features so as to achieve the mitigation targets with minimum economic costs.

Researches on the relationship between economic growth and environmental pressure mainly focus on the following several aspects. The first validates the existence of an inverted U-shaped relation between economic growth and environmental degradation indicators related to pollution (e.g., SO_2, NO_x), deforestation, and carbon emissions (Dinda 2004; Stern 2004; Kaika and Zervas 2013a, b; Sephton and Mann 2016; Liu et al. 2019). Whereafter, decomposition analysis, causality analysis, and cointegration analysis are further applied to illustrate the varied possible paths and outcomes within an EKC (Liu 2012; Ahmad et al. 2017; Riti et al. 2017; Mikayilov et al. 2018; Fan et al. 2019a). The second estimates the eco-efficiency, integrating economic, resource, and environmental aspects into a comprehensive index by applying the frontier approach (Picazo-Tadeo et al. 2012; Robaina-Alves et al. 2015; Beltrán-Esteve et al. 2017; Moutinho et al. 2018; Yang et al. 2020). The last one conducts the decoupling analysis to examine whether economic growth is heavily reliant on pollution discharge (Jorgenson and Clark 2012; Grand 2016). Among these three aspects, the first one cannot identify the contradiction characteristics between economic growth and environmental conservation in different phases. The latter two are able to provide a real-time dynamic index of the economy-environment contradiction, but the results estimated by the frontier approach are relative values and sensitive to the selection of input and output indexes. By contrast, the decoupling analysis is capable of reflecting the actual coupling status between economic growth and environmental pressure using absolute values that are stable and comparable in different periods. Nevertheless, as an isolated indicator, it fails to uncover the genuine efforts needed to achieve the decoupling

target and therefore requires other auxiliary approaches. Hereby, a comprehensive framework combining with other auxiliary means were developed to further identify the determinants affecting decoupling progress (Han et al. 2018; Cohen et al. 2019; Leal et al. 2019; Pao and Chen 2019).

Actually, the decoupling analysis has been viewed from different levels, such as the global level (Csereklyei and Stern 2015; Wu et al. 2018; Hao et al. 2019; Shuai et al. 2019), national level (Freitas and Kaneko 2011; Zhang and Da 2015; Roinioti and Koroneos 2017; Román-Collado et al. 2018; Wang and Wang 2019), regional level (Wang and Yang 2015; Yang et al. 2018; Han et al. 2018; Li et al. 2019; Cohen et al. 2019), and industrial level (Naqvi and Zwickl 2017; Engo 2019; Wang et al. 2020). However, the previous studies mainly focused on the CO_2 emissions from direct energy consumption (i.e., production-based emissions, PBE), which neglect off-site CO_2 emissions across supply chains to satisfy an economy's final consumption and assign the decoupling responsibility entirely to the production activities. In reality, economies can outsource energy- and emission-intensive industries to developing and undeveloped nations and import finished products from them to alleviate their own territorial environmental pressure. Production-based decoupling analysis always overlooks indirect emissions driven by final consumption and usually leads to an illusion of emission decoupling. It has been widely acknowledged that environmental pressure can be driven by the final consumption of finished goods and services and sustainable green consumption mode has been receiving increasing attention, meaning that decoupling progress focusing only on the production-side maybe not discernible and sufficient to achieve the desired sustainable development (Mont and Plepys 2008; Rocco et al. 2018; Yang et al. 2019). In other words, the patterns and degrees of final consumption can influence economic development and simultaneously shape the decoupling status between economic growth and CO_2 emissions across supply chains directly and indirectly. The decoupling responsibility of final consumption activities, namely consumption-based decoupling analysis, could be different from that of production-based analysis.

As a matter of fact, the consumption-based emissions (CBE) accounting has its roots in the academic community (Peters 2008; Gavrilova and Vilu 2012; Serrano and Valbuena 2017; Liu et al. 2018; Sudmant et al. 2018; Ninpanit et al. 2019; Wen and Wang 2020). In recent years, the consumption-based principle has also been gradually extended to the decoupling analyses regarding energy use in several studies (Moreau and Vuille 2018; Akizu-Gardoki et al. 2018; Sanyé-Mengual et al. 2019; Kan et al. 2019). However, taken as a whole, the consumption-based decoupling analysis is still lack in thorough research, and related studies are not available yet in China.

Above all, to the best of our knowledge, this study may be considered the first attempt to investigate the decoupling relationship between economic growth and CO_2 emission under production-based and consumption-based perspectives simultaneously. The research objective of this study is to explore whether China made efforts to decouple economic growth from CO_2 emissions under PBE and CBE perspectives, respectively, with a comprehensive application of input–output analysis, decomposition models, and decoupling index. This can impartially picture the decoupling degree in relation to the actual production and consumption activities, so as to allocate decoupling responsibilities between producers and final consumers more adequately and reasonably. Additionally, a decoupling effort model is constructed to further judge whether industrial sectors make efforts to reduce PBE and CBE or not in China. Overall, we expect to more comprehensively unveil the forces accelerating the decoupling progress in China from multiple perspectives, which makes it capable of designing targeted production- and consumption-oriented mitigation strategies.

The remainder of this paper is organized as follows. The "Methods" section presents the methodology for accounting for PBE and CBE of sectors, decomposition model of PBE and CBE, and decoupling index formulation. The "Data source" section shows the data sources. The "Results and discussion" presents results and related discussion. Conclusions and policy implications are given in the "Conclusions and policy implications" section.

Methods

Accounting for sectoral PBE and CBE

PBE means the direct CO_2 emissions arising from energy consumption in production activities, indicating a sector's role as the direct emitter, which ties the environmental responsibilities to producers (sectors) that provide goods and services. CBE means the total (both direct and indirect) upstream CO_2 emissions caused by the final demand of products and services from this sector, indicating a sector's role as the final consumer (Liang et al. 2014), which allocates the environmental responsibilities to where the goods and services are ultimately consumed (Wang et al. 2018; Fan et al. 2019b).

In this study, we use the environmentally extended input–output (EEIO) model to calculate the sectoral PBE and CBE. An input–output model describes the product transactions within an economy (Miller and Blair 2009), and therefore, we can construct the EEIO model given the sectoral direct CO_2 emissions as the satellite account. Assume that the whole economic system has n sectors, and define a $1 \times n$ emission intensity vector E to represent sectoral CO_2 emissions per unit total output, we can get the PBE and CBE of each sector by

Eqs. (1) and (2),

$$P = E\hat{x} \tag{1}$$

$$C = E(I-A)^{-1}\hat{Y} = EL\hat{Y} \tag{2}$$

where P is a $1 \times n$ vector denoting the sectoral PBE, x is a $n \times 1$ vector representing sectoral total output, the notation '^' means diagonalization of the vector; C is a $1 \times n$ vector representing the sectoral CBE, I is the $n \times n$ identity matrix, $A = [a_{ij}]$ is the $n \times n$ direct input coefficient matrix whose entry represents the goods produced by sector i that are required to produce unitary goods by sector j, Y is a $n \times 1$ vector denoting the sectoral final demand, and the $n \times n$ matrix $L = (I-A)^{-1}$ is the *Leontief inverse* matrix whose entry l_{ij} means the direct and indirect goods from sector i required to meet unitary final demand from sector j.

All the Chinese input–output tables are based on the competitive import assumption, meaning that the production technology of the homogeneous products from domestic production and imports are the same. It is common to deprive the imports used for intermediate production and the final demand from the transactions to investigate the actual emission situation only includes the domestic goods of China (Weber et al. 2008; Su and Ang 2013). The equation for calculating the domestic sectoral CBE can be expressed by Eq. (3):

$$C = E(I-A_d)^{-1}\hat{Y}_d = EL_d\hat{Y}_d \tag{3}$$

in which

$$A_d = \left(I-diag\left(y^{im}/\left(x+y^{im}-y^{ex}\right)\right)\right)\cdot A \tag{4}$$

$$Y_d = \left(I-diag\left(y^{im}/\left(x+y^{im}-y^{ex}\right)\right)\right)\cdot Y \tag{5}$$

where A_d and Y_d mean domestic direct input coefficient matrix and domestic final demand column vector, respectively; $L_d = (I-A_d)^{-1}$ is the *domestic Leontief inverse* matrix showing the domestic production technology; the $n \times 1$ vector y^{im} represents the imports, while the $n \times 1$ vector y^{ex} represents the exports. From the above equations, we can see that this approach of deprivation holds an assumption that each economic sector and final demand category uses imports of each corresponding sector in the same proportions.

Drivers decomposition of PBE and CBE

Generally, in order to quantify the contribution of different drivers to CO_2 emissions change, index decomposition analysis (IDA) and structural decomposition analysis (SDA) are two widely used approaches (Xu and Ang 2013; Jiang et al. 2015; Wang and Yang 2016; Wang et al. 2017; Chen et al. 2019). IDA can be applied to any available data at any level of aggregation, while SDA usually requires input–output tables (Hoekstra and Van der Bergh 2003; Su and Ang 2012).

Therefore, aiming to uncover the drivers for emission changes and decoupling status, we decompose PBE and CBE using IDA and SDA approaches here, respectively.

Drivers decomposition of PBE

The PBE of sector i (P_i) can be decomposed by the Kaya identity expressed by Eq. (6).

$$P_i = \frac{P_i}{EP_i} \cdot \frac{EP_i}{G_i} \cdot \frac{G_i}{G} \cdot \frac{G}{PO} \cdot PO \tag{6}$$

where EP_i refers to the total direct energy consumption in standard unit (PJ) of sector i, G_i represents the GDP of sector i, G denotes the total GDP of an economic system in a certain year, and PO stands for population size.

For simplification, Eq. (6) can be rewritten as follows:

$$P_i = SE_i \cdot EI_i \cdot YS_i \cdot PG \cdot PO \tag{7}$$

where SE_i is the synthesized emission coefficient of sector i (t CO_2/PJ), reflecting the energy mix, EI_i is the energy intensity of sector i (PJ/CNY), YS_i means the share of GDP of sector i in this economic system, reflecting the economic structure, PG refers to per capita GDP.

The total change of sectoral PBE between base period 0 and target period T can be expressed as:

$$\Delta P_i = SE_i^T \cdot EI_i^T \cdot YS_i^T \cdot PG^T \cdot PO^T - SE_i^0 \cdot EI_i^0 \cdot YS_i^0 \cdot PG^0 \cdot PO^0 \tag{8}$$

So, the effects of each driver variation on the changes of PBE in sector i can be decomposed into the sum of the contribution of each possible driver variation:

$$\Delta P_i = g(\Delta SE_i) + g(\Delta EI_i) + g(\Delta YS_i) + g(\Delta PG_i) + g(\Delta PO_i) \tag{9}$$

Based on the LMDI approach proposed by Ang (2005), the effect of different drivers can be calculated as follows:

Synthesized emission coefficient effect : $g(\Delta SE_i)$

$$= M(P_i^T, P_i^0) \ln(SE_i^T / SE_i^0) \tag{9a}$$

Energy intensity effect : $g(\Delta EI_i)$

$$= M(P_i^T, P_i^0) \ln(EI_i^T / EI_i^0) \tag{9b}$$

Economic structure effect : $g(\Delta YS_i)$

$$= M(P_i^T, P_i^0) \ln(YS_i^T / YS_i^0) \tag{9c}$$

Per capita GDP effect : $g(\Delta PG_i)$

$$= M(P_i^T, P_i^0) \ln(PG^T / PG^0) \tag{9d}$$

Population size effect : $g(\Delta PO_i)$

$$= M(P_i^T, P_i^0) \ln(PO^T / PO^0) \tag{9e}$$

and

$$M(P_i^T, P_i^0) = \begin{cases} (P_i^T - P_i^0)/(\ln P_i^T - \ln P_i^0), P_i^T \neq P_i^0 \\ P_i^T, P_i^T = P_i^0 \\ 0, P_i^T = P_i^0 = 0 \end{cases} \tag{9f}$$

Drivers decomposition of CBE

Similarly, in order to investigate the effect of socioeconomic driver variation on the changes of sectoral CBE, we decompose CBE using SDA approach as follows:

$$C = E \cdot L_d \cdot \hat{Y}_d = E \cdot L_d \cdot \hat{YS} \cdot PG \cdot PO \tag{10}$$

where $YS = [Y_{d,j}/Y_d]$ is a vector showing the final demand structure whose entry represents the share of final demand of a certain sector in total final demand, namely the same as economic structure from the expenditure approach perspective; and scalars PG and PO show the same meanings as in Eq. (7).

Then, CBE of sector j (C_i) can be obtained through:

$$C_j = \sum_i C_{ij} = \sum_i E_i \cdot l_{d,ij} \cdot YS_j \cdot PG \cdot PO \tag{11}$$

The total change of sectoral CBE between base period 0 and target period T can be expressed as:

$$\Delta C_j = \sum_i C_{ij}^T - \sum_i C_{ij}^0$$
$$= \sum_i E_i^T \cdot l_{d,ij}^T \cdot YS_j^T \cdot PG^T \cdot PO^T - \sum_i E_i^0 \cdot l_{d,ij}^0 \cdot YS_j^0 \cdot PG^0 \cdot PO^0 \tag{12}$$

Then the effects of each driver variation on the changes of CBE in sector j can be described as:

$$\Delta C_j = h(\Delta E_i) + h(\Delta l_{d,ij}) + h(\Delta YS_j) + h(\Delta PG_j) + h(\Delta PO_j) \tag{13}$$

where the individual effect of each driver changes while other drivers remain constant can be obtained through follows:

Emission intensity effect : $h(\Delta E_i)$

$$= \sum_i M(C_{ij}^T, C_{ij}^0) \ln(E_i^T / E_i^0) \tag{13a}$$

Production technology effect : $h(\Delta l_{d,ij})$

$$= \sum_i M(C_{ij}^T, C_{ij}^0) \ln(l_{d,ij}^T / l_{d,ij}^0) \tag{13b}$$

Economic structure effect : $h(\Delta YS_j)$

$$= \sum_i M\left(C_{ij}^T, C_{ij}^0\right) \ln\left(YS_j^T/YS_j^0\right) \quad (13c)$$

Per capita GDP effect : $h(\Delta PG_j)$

$$= \sum_i M\left(C_{ij}^T, C_{ij}^0\right) \ln\left(PG^T/PG^0\right) \quad (13d)$$

Population size effect : $h(\Delta PO_j)$

$$= \sum_i M\left(C_{ij}^T, C_{ij}^0\right) \ln\left(PO^T/PO^0\right) \quad (13e)$$

and,

$$M\left(C_{ij}^T, C_{ij}^0\right) = \begin{cases} \left(C_{ij}^T - C_{ij}^0\right)/\left(\ln C_{ij}^T - \ln C_{ij}^0\right), C_{ij}^T \neq C_{ij}^0 \\ C_{ij}^T, C_{ij}^T = C_{ij}^0 \\ 0, C_{ij}^T = C_{ij}^0 = 0 \end{cases} \quad (13f)$$

Decoupling index formulation

The decoupling index between economic growth and CO_2 emissions reflects the responsiveness of CO_2 emissions to unitary GDP change over a given period (Tapio 2005; Liang et al. 2014). It can be calculated by dividing the relative percentage change of CO_2 emissions with the relative percentage change of GDP, as Eq. (14):

$$\varepsilon = \frac{\%\Delta W}{\%\Delta G} = \frac{(W_T - W_0)/W_0}{(G_T - G_0)/G_0} = \frac{\Delta W/W_0}{\Delta G/G_0} \quad (14)$$

where ΔW and ΔG denote the relative change of CO_2 emissions and GDP from the base year 0 to target year T, respectively. It can be divided into eight cases (Vehmas et al. 2003, 2007; Tapio 2005), as shown in Fig. 1.

The efforts to reduce emissions from industrial production, both directly and indirectly, are mainly determined by optimizing energy mix and industrial structure, reducing energy intensity, and improving energy efficiency, as well as controlling the population, while the expanding economic output always shows facilitating effect (Diakoulaki and Mandaraka 2007). Therefore, the absolute effort (ΔAE) to reduce emissions of a certain sector over a given period from PBE and CBE perspectives (ΔAE_{Pi} and ΔAE_{Cj}) can be interpreted as the difference between sectoral CO_2 emissions change (ΔW, i.e., ΔP_i or ΔC_j here) and economic effect ($g(\Delta PG_i)$ and $h(\Delta PG_j)$) as:

$$\Delta AE_{Pi} = \Delta P_i - g(\Delta PG_i) = g(\Delta SE_i) + g(\Delta EI_i)$$
$$+ g(\Delta YS_i) + g(\Delta PO_i) \quad (15a)$$

$$\Delta AE_{Cj} = \Delta C_j - h(\Delta PG_j) = h(\Delta E_i) + h(\Delta l_{d,ij})$$
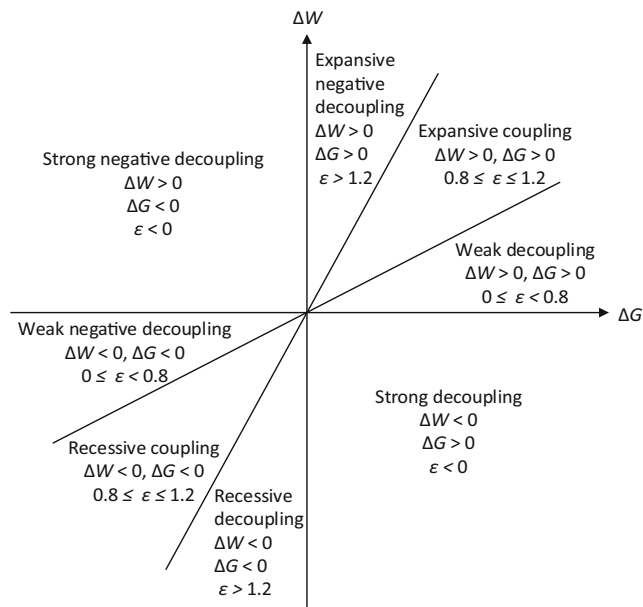$$+ h(\Delta YS_j) + h(\Delta PO_j) \quad (15b)$$

Fig. 1 Decoupling metrics between economic growth and CO_2 emissions

where ΔAE will be negative when the sum of the four inhibiting effects reducing CO_2 emissions. A negative ΔAE would not be necessarily associated with a negative ΔW as these reduction efforts may be waived by a high positive economic growth effect. Thus, a decoupling effort index D is built to uncover the absolute efforts to reduce emissions with response to economic growth from both PBE and CBE perspectives, as Eqs. (16a) and (16b):

$$D_{Pi} = -\frac{\Delta AE_{Pi}}{g(\Delta PG_i)} = -\frac{g(\Delta SE_i) + g(\Delta EI_i) + g(\Delta YS_i) + g(\Delta PO_i)}{g(\Delta PG_i)}$$
$$= -\frac{g(\Delta SE_i)}{g(\Delta PG_i)} - \frac{g(\Delta EI_i)}{g(\Delta PG_i)} - \frac{g(\Delta YS_i)}{g(\Delta PG_i)} - \frac{g(\Delta PO_i)}{g(\Delta PG_i)}$$

$$(16a)$$

$$D_{Cj} = -\frac{\Delta AE_{Cj}}{h(\Delta PG_j)} = -\frac{h(\Delta E_i) + h(\Delta l_{d,ij}) + h(\Delta YS_j) + h(\Delta PO_j)}{h(\Delta PG_j)}$$
$$= -\frac{h(\Delta E_i)}{h(\Delta PG_j)} - \frac{h(\Delta l_{d,ij})}{h(\Delta PG_j)} - \frac{h(\Delta YS_j)}{h(\Delta PG_j)} - \frac{h(\Delta PO_j)}{h(\Delta PG_j)}$$

$$(16b)$$

The last four terms in Eq. (16a) represent the relative contribution of the change of synthesized emission coefficient, energy intensity, economic structure, and population size to the decoupling effort progress from PBE perspective. Similarly, the last four terms in Eq. (16b) denote the relative contribution of the change of emission intensity, production technology, economic structure, and population size to the decoupling effort progress from CBE perspective. For the decoupling effort index D, there would be three categories:

(1) $D \geq 1$, "strong decoupling effort." It means the reduction effects of the four factors on emissions exceed the

facilitating effect of economic growth, that is to say, sectoral emissions decrease while the economy grows;

(2) $0 < D < 1$, "weak decoupling effort." It means the reduction effects of the four factors only offset part of emissions that originate from economic growth, which indicates that sectoral emissions increase and the economy grows as well;

(3) $D \leq 0$, "no decoupling effort." It means the speed of emissions growth exceeds that of economic growth, and variations of the four factors driver the emissions growth.

Data sources

In this study, we collected the 6 time-series Chinese input–output tables in 42-sector format for the year 2002, 2005, 2007, 2010 (41 sectors), 2012, and 2015 from the National Bureau of Statistics of China (NBSC 2006, 2008, 2010, 2013, 2015, 2018). In order to remove the influence of price deflations in different years, we converted all the input–output tables in current price into 2002 constant price based on the double deflation method (UNDESASD 1999), and price deflators were compiled according to the price indexes of different sectors collected from *China Statistical Yearbooks* (NBSC 2003-2016). There is a column named *Others* in input–output tables, which can be interpreted as an error term representing different data sources, and we got new sectoral total outputs after omitting the error items (Peters et al. 2007). Finally, we used the new sectoral outputs to normalize the input–output tables and emissions data.

Sectoral CO_2 emissions contain emissions from 17 kinds of fossil fuel combustion and 14 kinds of industrial product processes. The energy consumption data by energy type of different sectors were obtained from *China Energy Statistical Yearbooks* (NBSC 2014, 2016). The amounts of various industrial products were obtained from *China Statistical Yearbooks* (NBSC 2003-2016). We compiled sectoral direct CO_2 emissions inventories with the updated emission factors of various fossil fuels (Liu et al. 2015) and methods in Peters et al. (2006). For the CO_2 emissions from industrial processes, they were allocated into corresponding 4 industrial sectors in the final emissions by sectors (Peters et al. 2006). Sectoral total energy consumption (PJ) was compiled by the sum of each kind of fossil fuels multiplying by respective net calorific values. Sectoral GDP was derived from the final demands in input–output tables in constant price, which is compiled by the expenditure approach that comprises of household consumption, government consumption, gross capital formation, and export. Population size was obtained from *China Statistical Yearbooks* (NBSC 2003-2016). In order to make the classification of economic sectors in China's input–output tables

consistent with its energy consumption data, we aggregated all the emission data and input–output tables into a 28-sector format (see Appendix Table 1).

Results and discussion

### PBE and CBE during 2002–2015

The total industrial CO_2 emissions in China increased from 3,468.9 million tonnes (Mt) in 2002 to 9,134.0 Mt in 2015, with an annual growth rate of 7.7% (Fig. 2). A considerable growth happened before 2012 with an annual growth rate of 10.0%, thereafter, a smooth trend can be witnessed during 2012–2015 with the total emissions increased by only 1.5%. Not surprisingly, there existed significant heterogeneity in terms of sectoral CO_2 emissions estimated from production-based and consumption-based perspectives.

Under PBE perspective, *Production and supply of electricity and heat* (S22) always contributed most to the total emissions, followed by *Nonmetallic mineral products* (S13) and *Smelting and pressing of metals* (S14). These three sectors were the primary producers of CO_2 emissions in China with relatively steady contributions, ranging from 71.8% in 2002 to 77.8% in 2012 during the whole study period. In addition, CO_2 emissions from *Transport, storage, and post* (S26), *Chemical industry* (S12), *Other services* (S28), and *Processing of petroleum, coking, and processing of nuclear fuel* (S11) also accounted for certain proportions.

Under the CBE perspective, *Construction* (S25) ranked first all the time, followed by S28. The proportion of the former increased from 28.4% in 2002 to 39.3% in 2015 with only a slight decrease during 2002–2005, while that of the latter fell from 14.0% in 2002 to 11.4% in 2015. Besides, as three major heavy manufacturing sectors, CO_2 emissions from *Manufacture of general and special purpose machinery* (S16), *Manufacture of transport equipment* (S17), and *Manufacture of electrical machinery and equipment* (S18) made up a great joint proportion that increased from 11.9% in 2002 to 17.2% in 2015 with a peak of 21.1% in 2010.

S22 had always been the largest emission source of PBE in China but it was only responsible for about 4% of total CBE in most years. Due to the resource endowment, coal is the main primary energy in China and nearly 70% of electricity was generated by coal combustion. Even though the proportion of coal in energy mix declined in these years, it is still the most important primary energy in China. Fortunately, S22 had made some achievements in carbon abatement with a stable trend of CO_2 emission under the PBE perspective during 2012–2015 due to the improvement in power generation technology and expansion in renewable energy. PBE from S25 almost can be neglected, while CBE from it occupied the largest share, reflecting that the consumption demand of S25 exerted a significant pulling effect on

Fig. 2 China's sectoral PBE (a) and CBE (b) from 2002 to 2015
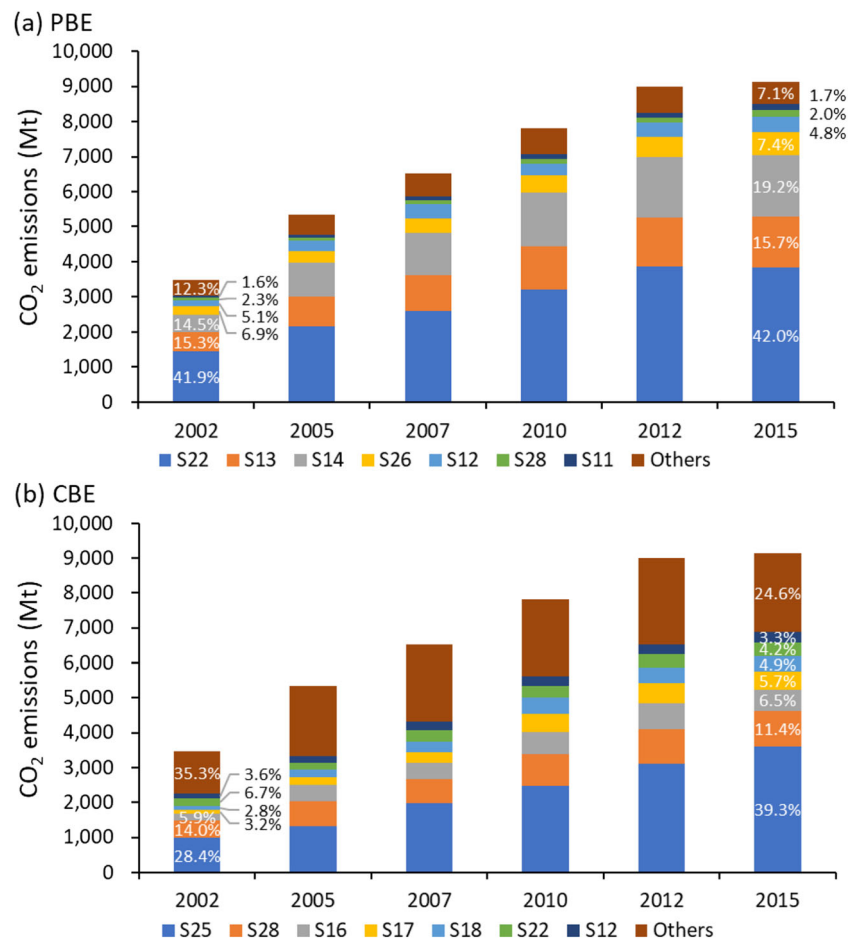
production activities of other sectors and the upstream inputs along the supply chains for S25 were energy- and emission-intensive. In addition, S28, neither a heavy nor an emission intensity industry, contributed a relatively great share to CBE, revealing that unfavorable consumption patterns existed in the pseudo-green service industry, which cannot be neglected in mitigation efforts.

Driving factors of CO_2 emissions changes

#### Contributions of drivers to CO_2 emissions changes at country level

The period-wise decomposition of CO_2 emission changes is depicted in Fig. 3. It is obvious that per capita GDP was the decisive factor driving the increase of CO_2 emissions during all sub-periods, and the growing population only exerted little impacts on increasing CO_2 emissions under both PBE and CBE perspectives. The impacts of the remaining factors were quite different and presented fluctuant trends.

Under the PBE perspective, changes in emission coefficient played a positive role in offsetting CO_2 emissions during 2007–2010 and 2012–2015, with decreasing effects of 232.7 Mt (−3.6%) and 42.8 Mt (− 0.5%). However, it prompted CO_2

emission growth to increase by 31% during 2002–2015, indicating the sectoral energy mix for production needs further improvements. Energy intensity was the strongest factor cutting down CO_2 emissions and roughly pictured N shape over the entire period. Specifically, it hindered the growth of CO_2 emissions during 2002–2007 and then prompted a significant increase during 2007–2012, but further turned back to reduce CO_2 emissions during 2012–2015 with a considerable reduction of 2,074.4 Mt (−23.0%). Economic structure was another significant offsetting factor, with a reduction effect of 1,540.9 Mt (−44%) over the whole study period, even it exerted little impacts on increasing CO_2 emissions during 2002–2007 and 2012–2015.

Under the CBE perspective, emission intensity has always had a positive role in decreasing CO_2 emissions except for the period 2010–2012. China has been constantly improving its energy efficiency and the efficiency gains had offset emissions by −137.0% during 2002–2015 if other drivers remain constant. China's emission changes can be considered a race between increasing consumption and efficiency gains (Peters et al. 2007) and emission/energy intensity shows convergence characteristics to some extent (Huang et al. 2019a, 2019b). However, efficiency loss led to CO_2 emissions rising by

Fig. 3 Decomposition of variations of Chinese CO_2 emissions from PBE (a) and CBE (b) perspectives during 2002–2015
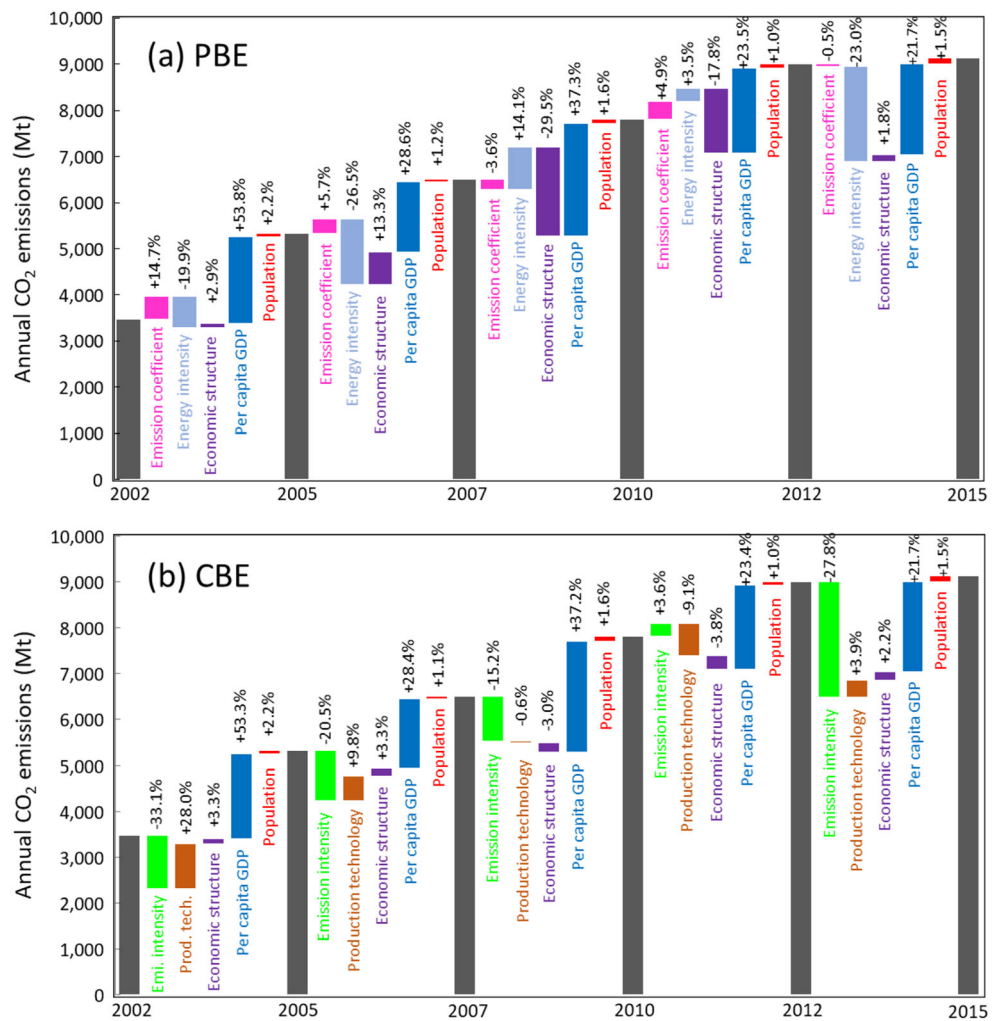
278.8 Mt (3.6%) during 2010–2012. Production technology was another significant factor responsible for the growth of CBE with a contribution of 49.2% during 2002–2015, even reduced CO_2 emissions during 2007–2012, indicating that the current production technology still needs to be upgraded and the innovative technologies should be developed immediately. The reduction effect of economic structure change was quite limited and varied over the periods without showing a clear tendency.

In sum, changes in energy intensity and emission intensity made the largest contribution to the decrease of PBE and CBE, respectively, indicating the energy-related technologies and policies had gained a better productive result in China. Chinese government conducted a four trillion yuan stimulus package in order to deal with the 2008 financial crisis. Massive investments mainly on infrastructures and constructions consumed great amounts of energy, causing ineffective utilization of energy resources and excessive emissions to a certain extent (Tang et al. 2016). The increasing per capita GDP exerted overwhelming effects on increasing CO_2 emission (246%) under PBE perspective. Meanwhile, it led to CO_2 emissions growth by 242% during

2002–2015 if other factors held constant under the CBE perspective. For demographic effect, it promoted the growth of PBE and CBE in all study intervals with extremely similar effects, but they were quite limited and much lower than the driving effect of per capita GDP change since Chinese government has controlled the population growth with a rate of 7% during 2002–2015. Actually, these two decomposed factors (per capita GDP and population) are the same, but their contributions to emission changes are slightly different. When conducting decomposition analysis, they are two different decomposition systems, it is common to get the quite similar effects of the same factor in different systems. Although China has slowed down its population growth, the improved living standard results in more demand for goods and services that consume energy during the production process and leading to greatly associated emissions along supply chains. Meanwhile, a growing number of people migrate from rural to urban areas along with the accelerating urbanization process in China, which is associated with the lifestyle transforming from low to relatively high energy intensity (Wang et al. 2018). Thus, public consciousness on sustainable consumption should be further guided and enhanced.

Contributions of drivers to CO₂ emissions changes at the sectoral level

From the sectoral perspective, regarding S22, energy intensity and economic structure exerted remarkable effects on decreasing its emissions under the PBE perspective (Fig. 4a). Nevertheless, change of synthesized emission coefficient of S22, reflecting the adjustment of the energy mix, drove the increase of CO₂ emissions during all the study intervals except 2007–2010, rooting in the emission coefficient of S22 increased by 72% during 2002–2015 with only a decrease of 4% during 2007–2010. For S13, changes of the former three factors exerted limited inhibiting effects during the whole period, and all of them were neutralized by the huge driving effect of the increasing per capita GDP. Changes in emission coefficient did not make much differences yet for S14, while energy intensity exerted fluctuated effects in different periods. Contrary to the inhibiting effect of economic structure change on offsetting emissions of S22 and S13, it promoted CO₂ emissions of S14 by 568.1 Mt (112.6%) during 2002–2015, which was the largest driving effect among all sectors.

Under CBE perspective, for S25, emission intensity changes curbed CO₂ emissions growth during all the intervals except 2010–2012 and ultimately resulted in a total decrease of 1,763.2 Mt (− 179.1%) (Fig. 4b). Changes of production technology and per capita GDP exerted apparently positive effects on the growth of CO₂ emissions all the time, with total effects

of 1,430.4 Mt (145.3%) and 2,941.2 Mt (298.8%), respectively. For S28, the declined emission intensity offset its CBE the most, and production technology changes also contributed certain decreasing effects during 2005–2015. The economic structure effect reduced emissions during 2002–2007 but drove emission growth during 2007–2015, which can be attributed to the increasing proportion of the tertiary industry in China. As for the other sectors, changes in both economic structure and production technology exerted fluctuated effects on their CO₂ emissions in different periods, resulting in overall non-significant impacts during the whole study period. The specific numbers showing sectoral emission changes in Fig. 4 can be found in the Supplementary Material.

The decoupling status analysis

Figure 5 plots the decoupling status for all sectors under both PBE and CBE perspectives during 2002–2015. It is encouraging that most sectors achieved weak decoupling during the whole study period, and some even achieved strong decoupling under both perspectives.

Under the PBE perspective, *Textile* (S7), *Manufacture of instrument and meter* (S20), *Production and supply of water* (S24), *Manufacture of communication equipment* (S19), and *Production and supply of gas* (S23) displayed strong decoupling, among which the former four are non-energy intensive industries and the last one is a clean-energy industry.
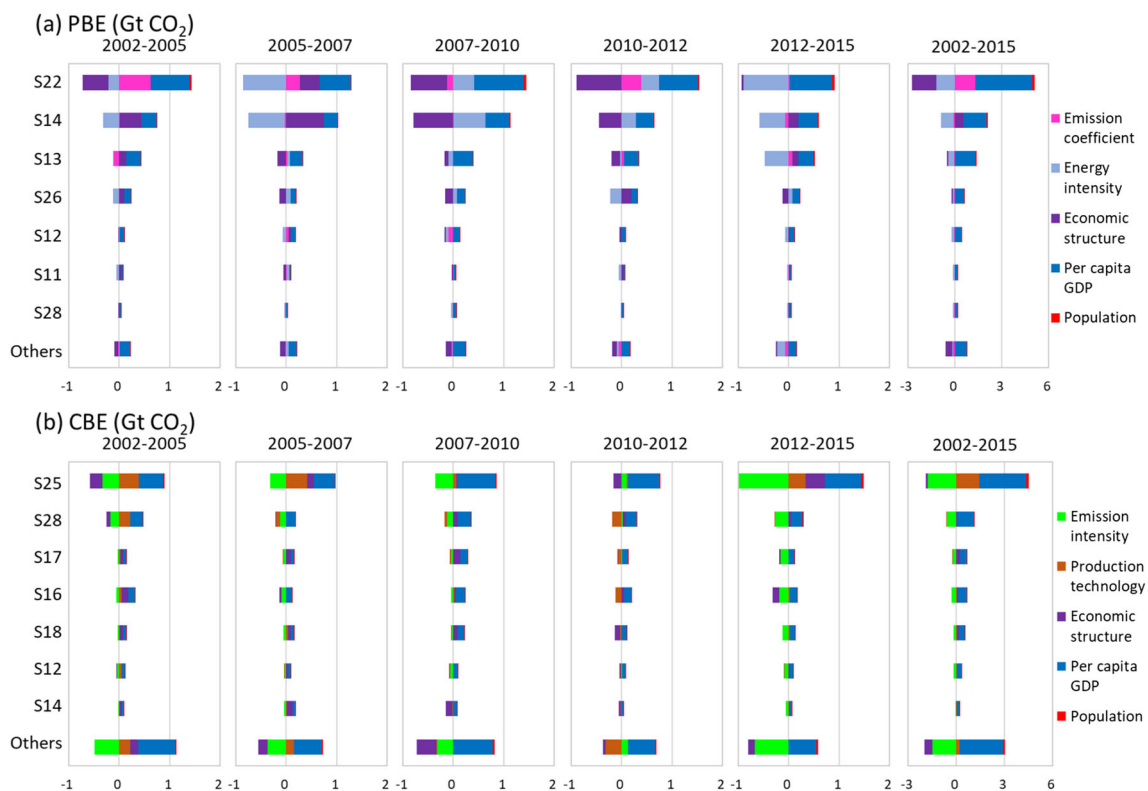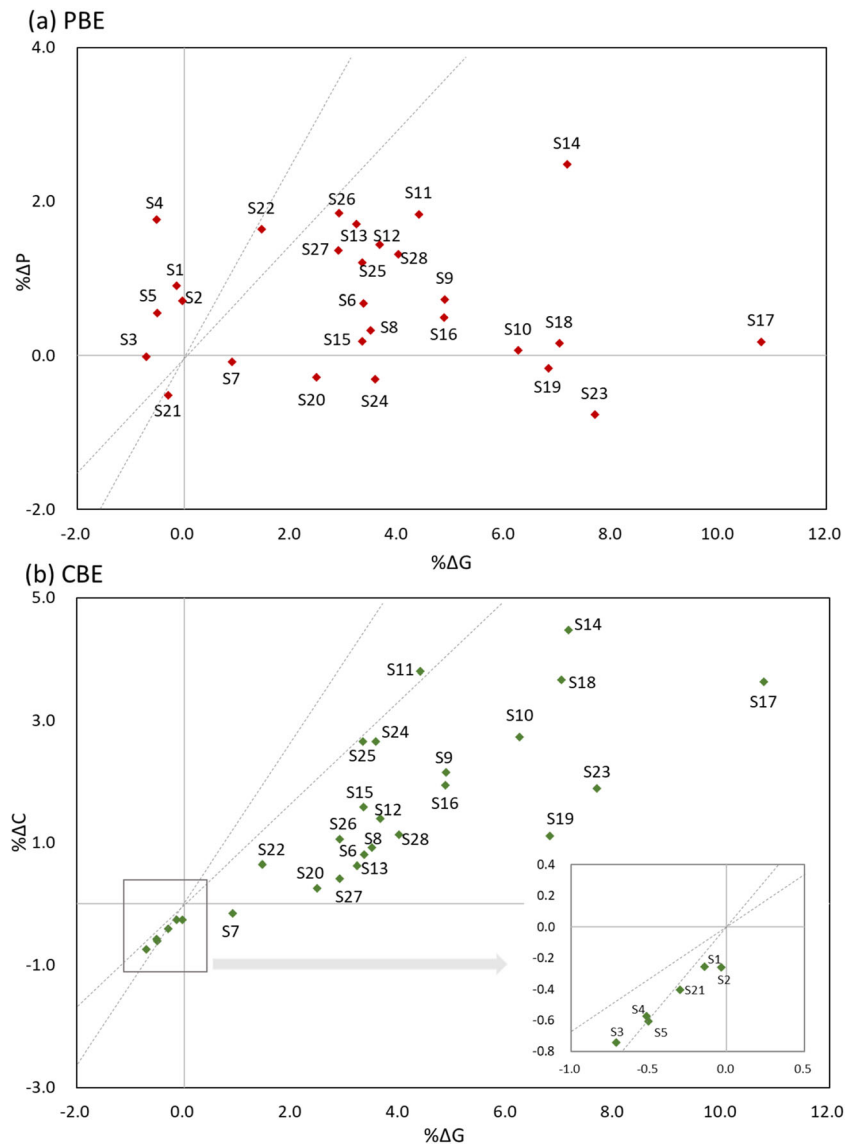

Fig. 4 Contributions of socioeconomic drivers to sectoral PBE (a) and CBE (b) in China during 2002–2015

Fig. 5 Tapio decoupling status for all sectors under PBE (a) and CBE (b) perspectives during 2002–2015

Apparently, *Production and supply of electricity and heat* (S22), the largest CO_2 emitting sector, was the only one evidencing expansive coupling and even showing a tendency towards expansive negative decoupling. In fact, China's fossil power generation technologies had achieved remarkable effects of carbon abatement around the world during the past decade, and therefore the estimated result proves that other ways such as developing renewable energy or carbon capture and storage technology may be the most effective means to reduce CO_2 emissions from S22 in the future.

Additionally, it should be noted that *Agriculture, forestry, animal husbandry, and fishery* (S1), *Mining and washing of coal* (S2), *Mining and processing of metal ores* (S4), and *Mining and processing of nonmetallic ores and other ores* (S5) presented strong negative decoupling, noting that production activities of these sectors consumed large amounts

of fossil energy while their economic outputs were shrinking. S1, a key but relatively weak industry in China, was placed under multilateral trade mechanisms and increasingly fierce competition with the accession into the WTO, leading to the continuous decreasing proportion in the national economy year by year. S2, S4, and S5, three mining industries, experienced the period of phasing out backward production facilities and reducing overcapacity during the past decade, resulting in a decline of industrial production. Nevertheless, the CO_2 emissions from these four sectors underwent significant increases, indicating they still need to further enhance energy utilization efficiency.

Extraction of petroleum and natural gas (S3) and *Other manufacture and scrap* (S21) exhibited weak negative decoupling and recessive decoupling, respectively, reflecting both CO_2 emissions and economic output of these two sectors declined

during the study period. China has been constantly importing great amounts of crude oil and natural gas and the external dependence is continuously increasing in the recent decade, resulting in that China has become the top importing nation of oil since 2017 and natural gas since 2018, respectively (CNPC 2019). Correspondingly, the domestic production activities of S3 and associated emissions both decreased. As for S21, owing to its small proportion and decreased production in the national economy, it recorded recessive decoupling together with the improved disposal efficiency of waste discharges resulting from technological advancement during 2002–2015.

Under the CBE perspective, it is evident that most sectors achieved weak decoupling and no sector achieved strong negative decoupling. Instead, S1, S2, S5, and S21 exemplified recessive decoupling, while S3 and S4 presented recessive coupling, meaning that both economic outputs and CO_2 emissions arising from the consumption of these sectors decreased during the overall period. Additionally, strong decoupling also can be observed in S7, indicating that CO_2 emissions arising from both production activities and consumption demands decreased along with the increase of economic output. S11 presented expansive coupling with an index of 0.87 which was approximate to weak decoupling. In particular, it is worth noting that S25, the largest CBE emitter, achieved weak decoupling over the entire period, with an index of 0.79. Similarly, it also showed a tendency towards expansive coupling and therefore should be taken seriously in the future.

The decoupling efforts analysis

According to Eqs. (16a)–(16b), we can obtain the decoupling effort indexes for all sectors and identify the relative contribution of each factor to the decoupling progress.

Decoupling effort analysis under PBE perspective

All sectors had made efforts to break the links between economic production and CO_2 emissions under the PBE perspective (Fig. 6a). Among them, *Production and supply of gas* (S23) performed the best, with the decoupling effort index of 1.99 (Fig. 6b), followed by *Other manufacture and scrap* (S21), *Production and supply of water* sector (S24), *Manufacture of instrument and meter* (S20), *Manufacture of communication equipment* (S19), *Textile* (S7), and *Extraction of petroleum and natural gas* (S3) whose decoupling effort indexes were above 1.0, indicating all of these sectors had made strong decoupling efforts. *Papermaking* (S10), *Manufacture of electrical machinery and equipment* (S18), *Manufacture of transport equipment* (S17), *Metal products* (S15), and *Manufacture of wearing apparel* (S8) showed relatively better performances, with the indexes above 0.8. By contrast, *Processing of petroleum and nuclear fuel* (S11), *Transport, storage, and post* (S26), and *Smelting and pressing*

of metals (S14) performed the worst with the indexes below 0.3. All the rest sectors had the decoupling effort indexes ranging from 0.3 to 0.7. Additionally, almost all sectors can be witnessed an improvement in the decoupling effort level except S3, S21, S25 (*Construction*), and S28 (*Other services*). Also, great fluctuation can be seen in S2 (*Mining and washing of coal*), S15, S19, S21, and S23. As the top three PBE emitters, S22 (*Production and supply of electricity and heat*), S13 (*Nonmetallic mineral products*), and S14 made remarkable decoupling progress, with their indexes almost standing on 1.0 during 2012–2015.

In terms of the decomposition results for the decoupling progress, it is evident that the effects of energy intensity change contributed greatly to the decoupling progress for all sectors except *Agriculture* (S1), the mining sectors (S2–S5), and *Other manufacture and scrap* (S21). The decoupling progress of these six exceptions was mainly attributed to economic structure change effects ranging from 86% in S21 to 502% in S4. The change of emission coefficient also contributed to the decoupling effort progress in most sectors, while it exerted little effects to block decoupling effort progress in S1, S2, S11, and S22. Population size was the only factor hindering the decoupling effort progress in all sectors, but its effect was quite limited.

Decoupling effort analysis under CBE perspective

The decoupling effort indexes under the CBE perspective are shown in Fig. 7, and it reveals a totally different picture from those under the PBE perspective. It can be seen that apart from S11, S14, S17, and S18, all the other sectors had achieved the decoupling progress, with their decoupling effort indexes greater than 0 during 2002–2015 (Fig. 7b). S1, S2–S5, S7, and S21 performed the best, with their decoupling effort indexes above 1.0, followed by S20 and S27 (*Wholesale, retail trade, hotel, and catering services*) whose decoupling effort indexes were higher than 0.7. Additionally, it is noticeable that most sectors witnessed an improvement in the decoupling effort level, except that S2, S5, S21–S25. Meanwhile, as the two largest CBE sectors, neither S25 nor S28 had made significant decoupling effort progress, with their decoupling effort indexes of 0.11 and 0.48, respectively.

In terms of the decomposition results for the decoupling progress, it is obvious that the declined emission intensity was conducive to the decoupling effort in all sectors with similar effects, while production technology changes almost restricted the decoupling progress for all sectors except S6, S17, S19, S20, S27, and S28. The changes in economic structure and population respectively exerted roughly the same effects on the decoupling progress as those under PBE perspective. In addition to great efforts exert in the aforementioned six exceptions (S1, S2–S5, S21), the change of economic structure also exerts certain effects on the decoupling progress in S7, S20, and S22.
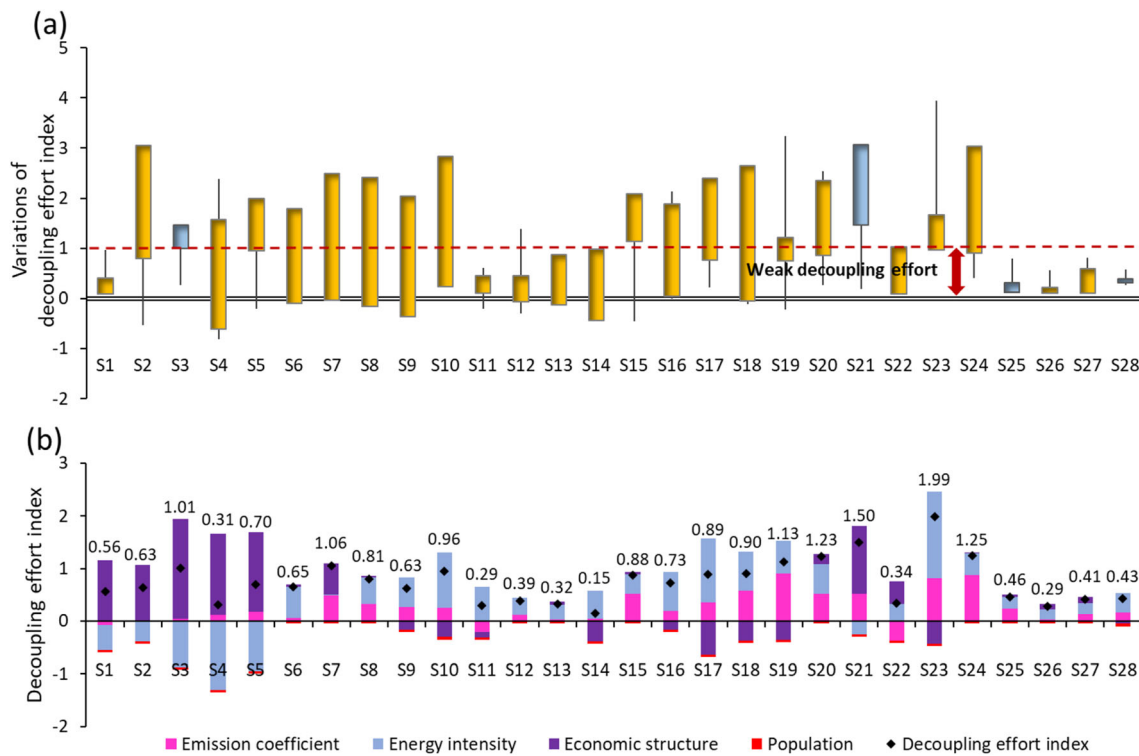
Fig. 6 Decoupling effort indexes under PBE perspective. **a** Fluctuation trend of decoupling effort index of each sector during the five study periods (2002–2005, 2005–2007, 2007–2010, 2010–2012, 2012–2015). The yellow bar indicates the decoupling effort index of the first period (2002–2005) is higher than that of the last period (2012–2015), while the blue bar means the opposite. The length of each vertical line illustrates the high-low index range among the five periods, the top of the line shows the highest index while the bottom shows the lowest. **b** Decoupling effort indexes of sectors (black spots) induced by the decomposed factors during 2002–2015, numbers at the top of bars are the decoupling effort indexes for sectors corresponding to the black spots

Conclusions and policy implications

The decoupling analysis has been intensively studied by numerous researchers, whereas little attention has been paid to the economic growth and CO_2 emissions across supply chains as a result of final consumption. It is necessary to consider both production- and consumption-based CO_2 emissions so as to correctly identify the decoupling responsibilities associated with changes in production activities and consumption patterns. In this paper, we apply the input–output analysis combined with decomposition analysis and the Tapio index to investigate whether China made efforts to decouple economic growth from CO_2 emissions under both production- and consumption-based perspectives. Results in this study are able to provide targeted supports and foundations for further formulation of emission reduction policies as well as the cultivation of green production and sustainable consumption patterns. The main conclusions are as follows:

[1] The total amount of industrial CO_2 emissions in China increased from 3,468.9 Mt in 2002 to 9,134.0 Mt in 2015, with an average annual growth rate of 7.7%. *Production and supply of electricity and heat* (S22) and *Construction* (S25) contributed most to the PBE and CBE, respectively.

[2] Per capita GDP had always been the largest driver leading to CO_2 emissions growth under both PBE and CBE perspectives, while these effects were mainly offset by the changes of energy intensity and economic structure under PBE perspective and emission intensity under CBE perspective. Emission coefficient and production technology changes drove certain PBE and CBE growth, respectively, during the whole period, but offset emissions during certain subperiods. Population increase promoted both PBE and CBE up all the time, but its effects were quite limited.

[3] Three-quarters of sectors had achieved weak decoupling even strong decoupling under both PBE and CBE perspectives during 2002–2015. *Agriculture, forestry, animal husbandry, and fishery* (S1), *Mining and washing of coal* (S2), *Extraction of petroleum and natural gas* (S3), *Mining and processing of metal ores* (S4), and *Mining and processing of nonmetallic ores and other ores* (S5) evidenced negative decoupling under the PBE perspective and recessive (de)coupling under CEB perspective, respectively. Additionally, it should be noted that *Other manufacture and scrap* (S21) and *Textile* (S7) were the only two sectors presenting recessive decoupling status and strong decoupling status, respectively, during 2002–2015 under both PBE and CBE perspectives.
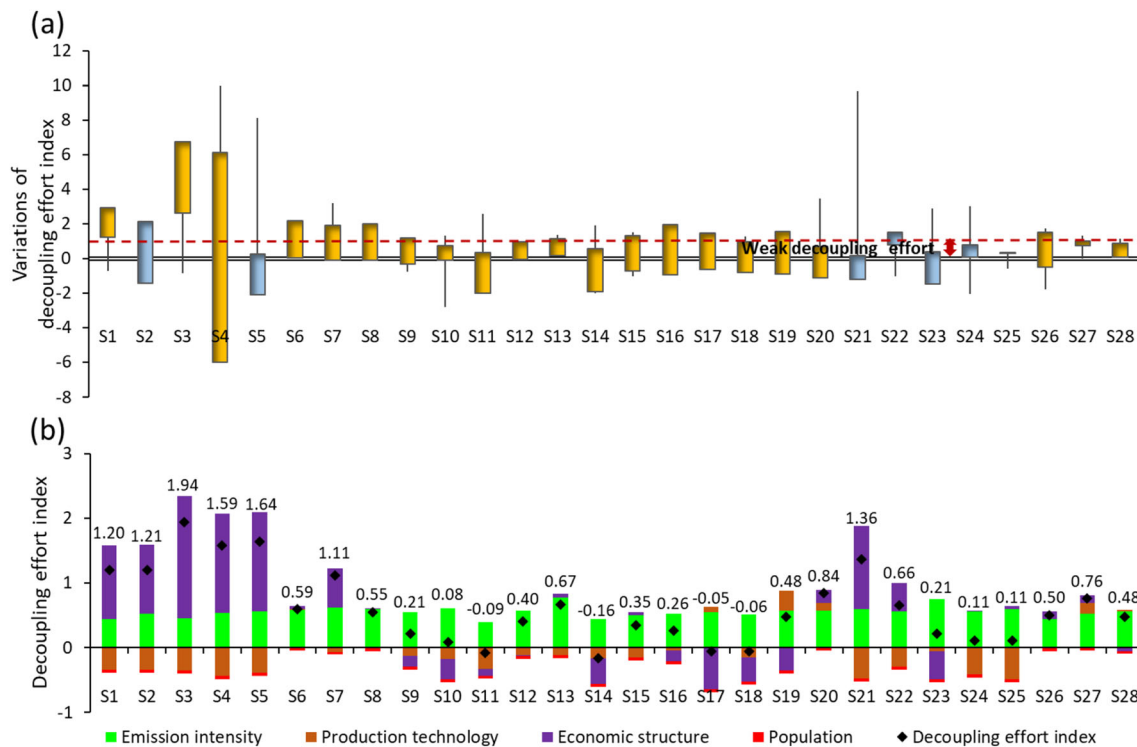
Fig. 7 Decoupling effort indexes under the CBE perspective. **a** Fluctuation trend of decoupling effort index of sector during the five study periods, **b** decoupling effort indexes of sectors during 2002–2015. Elements in this figure show the same meanings as those in Fig. 6

[4] The decoupling effort indexes showed remarkable differences under the two perspectives. All sectors had made efforts to break the links between economic output and CO_2 emissions under PBE perspective, while *Processing of petroleum and nuclear fuel* (S11), *Smelting and pressing of metals* (S14), *Manufacture of transport equipment* (S17), and *Manufacture of electrical machinery and equipment* (S18) failed to achieve the decoupling effort progress under CBE perspective. Mitigation effect of declined energy intensity contributed to the decoupling progress in most sectors under the PBE perspective. By contrast, the decoupling effort progress made by declined emission intensity can be observed in all these sectors under the CBE perspective.

According to the estimated results, some policy suggestions can be put forward. Firstly, the Chinese government has carried out packages of mitigation strategies and regulations to tackle the issue of CO_2 emissions, however, nearly all measures focus on emissions emitting from production activities, and emissions driven by final consumption of goods and services have not been effectively controlled. Our results showed that the decoupling status for PBE was better than that for CBE during the study period, and therefore the future carbon management framework should allocate responsibilities for emission reduction between the producers and final consumers more adequately, with clearly defined boundaries and dynamic phase-in emissions targets. Secondly, *Production and supply of electricity and heat* and *Construction*, the largest contributors of PBE and CBE,

respectively, just made weak decoupling effort during the past decade, and thus should be the focuses of energy conservation and emission reduction in the future and their growth rates should be controlled. It is suggested that the government should actively promote the supply-side reform management in the electricity sector through optimizing the structure of thermal power generation and power generation, and strengthen the demand side management in the construction sector through guiding reasonable consumption concepts and behavior. Thirdly, the economic restructuring exerted a weak even negative effect on decoupling progress for most sectors. Therefore, the government needs to further adjust and optimize the industrial structure reasonably to promote the decoupling of economic growth from CO_2 emissions. The main adjustment direction of the industrial structure asks to compress the industrial scale and adjust the industrial internal sector structure reasonably. From the defusing overcapacity aspect, we suggest that the detailed defusing projects which point to the provincial level should be promulgated to intensify the resolving effort a step further. Fourthly, the current production technology is not environmental-friendly enough in China and has been a significant factor blocking the decoupling progress. We suggest establishing a whole industrial chain management mechanism and improve the technology and efficiency for the large carbon emitters as soon as possible.

Overall, this study provides a new dimension to explore the decoupling CO_2 emissions from economic growth in China. However, regional disparities are not considered. Future emission mitigation plans should be more industry- and region-

oriented, with clearly defined boundaries for relevant industries and dynamic phase-in emissions targets in different regions. In other words, it will be more appropriate to allocate carbon emission quotas with region-specific responsibilities by considering regional development stage, resource endowments, strategic position, and ecological protection. Accordingly, our future study will further apply the multi-regional input-output table to investigate the decoupling status in different regions under both production-based and consumption-based perspectives.

Appendix. Sector classification

Table 1 Sector classification of the Chinese economy

Sector code	Sector name
S1	Agriculture, forestry, animal husbandry, and fishery
S2	Mining and washing of coal
S3	Extraction of petroleum and natural gas
S4	Mining and processing of metal ores
S5	Mining and processing of nonmetallic ores and other ores
S6	Manufacture of foods and tobacco
S7	Textile
S8	Manufacture of wearing apparel, leather, feather and its products
S9	Processing of timber and manufacture of furniture
S10	Papermaking, printing, and manufacture of articles for culture, education and sports activities
S11	Processing of petroleum, coking, and processing of nuclear fuel
S12	Chemical industry
S13	Nonmetallic mineral products
S14	Smelting and pressing of metals
S15	Metal products
S16	Manufacture of general and special purpose machinery
S17	Manufacture of transport equipment
S18	Manufacture of electrical machinery and equipment
S19	Manufacture of communication equipment, computer, and other electronic equipment
S20	Manufacture of instrument and meter, and machinery for cultural activity and office work
S21	Other manufacture and scrap
S22	Production and supply of electricity and heat
S23	Production and supply of gas
S24	Production and supply of water
S25	Construction
S26	Transport, storage, and post
S27	Wholesale, retail trade, hotel, and catering services
S28	Other services

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