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Changes in China's Production-Source CO_2 Emissions: Insights from structural decomposition analysis and linkage analysis[*]

By Ning Chang[a] & Michael L. Lahr[b]

ABSTRACT: This paper presents an input–output based methodology – structural decomposition analysis (SDA) plus linkage analysis, for identifying the key factors and sectors that affected production-source CO_2 emissions in China. The proposed methodology extends the SDA to account for the import substitution effect within an open economy such as China and incorporates the emission linkage by which the effect of the input mix on CO_2 emissions can be understood in depth. Empirical results indicate that, between 2005 and 2010, improving emission intensity and input intensity had helped to reduce CO_2 emissions; meanwhile, capital investment explained the majority of the increases in CO_2 emissions brought about by final demand, and import substitution was also observed to increase CO_2 emissions. Moreover, nine key emission sectors have been identified, and in this regard, domestic inputs became more CO_2-intensive in 2010 than it was in 2005.

Key Words: CO_2 emissions; structural decomposition analysis; linkage analysis; China

1. INTRODUCTION

Lately, reducing the CO_2 emissions associated with production has garnered considerable attention. The reason for the concern in climate change is that about 97 percent of actively publishing climate researchers support tenets of anthropological climate change as outlined by the Intergovernmental Panel on Climate Change (Anderegg et al., 2010). Further, CO_2 is the main anthropological greenhouse gas that is contributing to climate change. Thus, the issue is particularly poignant for China since its CO_2 releases amount to 30 percent of global emissions (Olivier et al., 2015), a share that continues to climb. Even before these announcements, however, China made efforts to reduce carbon emissions a high priority (Wang et al., 2015). Still, a

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report by the Commonwealth of Australia (2015) for the United Nations Framework Convention on Climate Change suggests that China's aggregate CO_2 emissions could rise to 150 percent of present levels by 2030. Faced with such intense pressure, China’s government announced its intention to reduce carbon intensity (the amount of CO_2 emitted per unit of GDP) by 60-65% of the 2005 level by 2030 (National Development Reform Commission, 2015). Also by 2030, China intends to increase its nonfossil energy share of total primary energy supply to around 20% and to increase its forest stock volume by 4.5 billion cubic metres, compared to 2005 levels. Note that 2030 is also the year by which China proposes to reach its peak emissions levels (Milman, 2015). In order to recognize whether or not China can achieve these various targets and whether the proposed measures are sufficient, an understanding of the origins of China’s rapid rise to become the world’s top CO_2 emitter is desperately needed. Getting a solid grasp of the causes of recent change will undoubtedly provide insight into the set of policies that can enable a transition to a lower-carbon future in China.

A growing body of literature has been accumulating that attempts to identify causes of changes in China’s CO_2 emissions. A key approach has been decomposition analysis. Several studies have used index decomposition analysis (IDA) to quantify the relative contribution of different factors to aggregate CO_2 emission change and to CO_2 intensity from regional (Wu et al., 2005; Wang et al., 2005; Liu et al., 2010) and sectoral (Fan et al., 2007; Xu et al., 2014; Li et al., 2015) perspectives. Generally the components of change employed in these analyses have been economic effects, energy intensity effects, structural effects, and population effects, although others have been employed. But a different approach, structural decomposition analysis (SDA), has been applied to account for the proximate changes in China’s CO_2

emission in somewhat more detail. The components in this form analysis include input mix, the mix and internal composition of final demand, industry mix, and emissions per unit of production. SDA can take on both additive (e.g., Peters et al., 2007; Guan et al., 2008; Tian et al., 2013; Guo and Liu, 2014) and multiplicative (e.g., Zhang and Lahr, 2014; Su and Ang, 2015) forms and are based upon the input-output framework.

In addition to the IDA and SDA approaches, a new decomposition analysis based on the production theory (PDA) has been gaining some attention (Zhou and Ang, 2008; Zhang et al., 2012; Wang et al., 2015; Yuan and Zhao, 2016). It combines distance functions and data envelopment analysis (DEA) to decompose aggregate CO_2 emission changes into several factors.

The present paper is inspired by several SDA studies (Zhang, 2009; Guan et al., 2009; Minx et al., 2011; Zhang and Qi, 2011) on China's production-source CO_2 emissions. These studies have tended to highlight the importance of technology change (such as emissions intensity) in reducing China's CO_2 emissions and significance of the nation's rising wealth (as reflected in components of final demand) as a pressure that increases CO_2 emissions in China. But there has been some disagreement about the role of the production structure (usually denoted by the Leontief inverse). Zhang (2009) notes that the change in the production structure was an important driving force behind China's decarbonising trend since 1992, especially from 2002 to 2006. Zhang and Qi (2011) also found that the production structure was key in reducing CO_2 emissions in China from 1997 to 2002. Contrarily, Guan et al. (2009) observed production structure changes as a significant emission driver in China for the period 2002 to 2005. Minx et al. (2011) concur, asserting that changes in the production structure caused a steep rise in CO_2 emission in China between 2002 and 2007.

The relative role of production structure in CO_2 change is of great interest for the governments and policy makers in China. As it is quite centrally controlled, China's government can actually be quite influential in adjusting its domestic industry set (Bruyn, 1997). Interestingly, changes in the production structure may indicate production efficiency improvements, but they may also be attributable to import substitution or to changes in product mix within an industry. Decomposition studies typically remove imports from the input-output data, and therefore fail to investigate the full set of possible underlying sources of the changes in the production structure and, hence, the associated CO_2 emissions. This may explain why the existing literature on the subject is inconsistent with respect to change in China's CO_2 emissions. It is noteworthy that, only a few SDA studies on emissions have further decomposed the production structure effect into various sub-effects, such as Chang et al. (2008) for Taiwan, Lim et al. (2009) for Korea and Okushima and Tamura (2010) for Japan. To date, no similar SDA study on China's CO_2 emissions has been published. This paper aims to fill this gap.

While SDA findings can help identify what causes change and in what industries change was greatest, it does not point out the sectors with the greatest capacity to pollute. The identification of emission linkages supports this goal. Previous work on linkage analysis has focused on economic issues (see Sonis et al., 1995; Dietzenbacher and van der Linden, 1997; Sonis and Hewings, 1999; Miller and Lahr, 2001; and Tzouvelekas, 2002, for summaries) but has been more recently extended to examine pollutant emissions (see, e.g., Lenzen, 2003; Sánchez-Chóliz and Duarte, 2003; Tarancon and del Rı′o, 2007). Generalised linkage analysis yields insight about forward and backward resource use and pollutant emission effects associated with a given sector. In the light of being able to account for embodied emissions in production process, linkage analysis gives a deeper understanding of the effects of the production structure on CO_2 emissions. From a policy standpoint, it yields a systemic perspective on a sector's contribution to CO_2 emissions.

This paper attempts to present an input-output based approach—SDA plus linkage analysis, to identify the key factors and sectors that affect production-source CO_2 emissions and provide better information than previously has existed that can help to identify effective emissions mitigation strategies for China. It is worth pointing out that Wood (2009) already combined SDA and linkage analysis by adopting the linkage terms into the SDA formula as two components. But this paper does so in two phases: by explaining the associated changes in the production structure and then by identifying the key emission sectors in Chinese economy.

First we use SDA to elucidate historical drivers of change. To be specific, the changes in China's production-source CO_2 emission are classified into six main components: emission intensity, input intensity, import substitution, the composition and allocation of final demand, and the level of final demand. Afterwards, linkage analysis is used to identify the prospective direction of structural adjustment policies that emanate from the SDA findings.

This paper extends SDA studies in two ways. First, it examines changes in the production structure as decomposed into two sub-effects to identify the relative channels through which changes in production structure are affecting CO_2 emissions—imports or domestic production. Second, emission linkages are examined to get a better handle on the polluting character sectors and to identify those sectors that are most responsible, in one way or another, for the most CO_2 emissions.

Combined the results of SDA and linkage analysis will shed light on the mechanisms of change for production-source CO_2 emissions. By understanding these mechanisms, China should be able to formulate better carbon mitigation policies.

The paper is structured as follows. Section 2 describes the SDA method that is used to quantify the effects of the six examined components of CO_2 emissions. It also interprets and discusses the contributions of these components. Thereafter, the employed generalised emission linkage measures are laid out and China's key emission sectors are identified and discussed. Section 3 presents a case study of China, including the employed data and main empirical results. Section 4 provides the conclusions and policy implications.

2. METHOD

The input-output (IO) method as originally formalised by Leontief (1941) is an effective tool for tracking the direct and indirect CO_2 emissions flows of an economy. In an open economy, like China's, the distinction between imported and domestically produced inputs is necessary. That is, to avoid overestimating the multiplier effects in the economy, the technology coefficient matrix **A** of the standard IO model must be bifurcated into $\mathbf{A}^d$ and $\mathbf{A}^m$, matrices of technology coefficients that measure the domestic (*d*) and imported (*m*) inputs by industry, respectively. Unfortunately, Chinese IO tables do not distinguish the inputs in this fashion. Instead imports are only defined by demanding industry as a column within final demand. So, instead, it is assumed that imports are allocated as an equal share of the sales of a sector (the row of **A)**. This assumption implies that imports substitute for domestic equivalents and that imported goods are proportional in domestic use for final deliveries or intermediate use. Hence, $\mathbf{A}^d$ and $\mathbf{A}^m$ can be calculated using the formulas:

$$\mathbf{A}^m = \hat{\mathbf{R}}\mathbf{A} \tag{1}$$

$$\mathbf{A}^d = (\mathbf{I} - \hat{\mathbf{R}})\mathbf{A} \tag{2}$$

where $\hat{\mathbf{R}}$ is an $n \times n$ matrix with the vector **r** on the diagonal and zeros elsewhere, and where **r** is a vector composed of elements calculated by

$$r_{ii} = \frac{m_i}{m_i + x_i} \tag{3}$$

where m_i is imports of sector i and x_i is domestic production of sector i.

With this bifurcation, SDA and emission linkage analysis can be more accurately depicted. For example, the direct and indirect CO_2 emissions that arise from productive activities within an economy can now be calculated as:

$$C = \mathbf{c}(\mathbf{I} - \mathbf{A}^d)^{-1}\mathbf{F}^d\mathbf{i} = \mathbf{cLF}^d\mathbf{i} = \boldsymbol{\mu}^c\mathbf{F}^d\mathbf{i} \tag{4}$$

where C indicates total domestic CO_2 emissions, **c** is vector of direct emission coefficients for n industries (in terms of CO_2 emissions per unit of output), $\mathbf{L} = (\mathbf{I} - \mathbf{A}^d)^{-1}$ is the domestic total requirements matrix so that $\boldsymbol{\mu}^c = \mathbf{c}(\mathbf{I} - \mathbf{A}^d)^{-1}$ is the vector of emissions multipliers for each of n industries and with elements that show the sum of direct and indirect CO_2 generated per unit of domestic final demand, $\mathbf{F}^d$. Here $\mathbf{F}^d$ is an $n \times 3$ matrix; that is, there are three final demand sectors. Also, here and throughout this paper **i** is a summation vector of appropriate dimension.

Based on the generalised environmental input-output model described in equation (4), we can now examine the SDA approach that is applied. An assessment of linkages and key sectors for CO_2 emissions follows.

2.1 Structural decomposition analysis of CO_2 emissions

SDA attributes CO_2 emissions to possible causal determinants. Through a typical set of SDA equations each determinant is attributed its respective contribution to emissions over time *ceteris paribus*. Early on in SDA usage it became clear that a large number of acceptable decompositions existed for any given set of determinants. Fortunately, after analysing the sensitivity of results to alternative decompositions, Dietzenbacher and Los (1997; 1998) found that the average of all the forms was approximated very well by the average of just two extreme or polar forms. Since then De Haan (2001) has shown that, in fact, the average of any two mirror decompositions provides a reasonable estimate. The average of two polar decompositions is used here.

Supposing that the total amount of CO_2 emission from production activities at time 0 and 1 are C_0 and C_1, respectively, and following the two polar decompositions of Dietzenbacher and Los (1998), changes in CO_2 emissions, $\Delta C = C_1 - C_0$, can be decomposed, additively, into following formula:

$$\Delta C = [0.5 \cdot \boldsymbol{\Delta\mu}^{\mathbf{c}}(\mathbf{F}_0^{\mathbf{d}} + \mathbf{F}_1^{\mathbf{d}})\mathbf{i}] + [0.5 \cdot (\boldsymbol{\mu}_0^{\mathbf{c}} + \boldsymbol{\mu}_1^{\mathbf{c}})\boldsymbol{\Delta}\mathbf{F}^{\mathbf{d}}\mathbf{i}] \tag{5}$$

The first term on the right-hand side (RHS) represents the change in CO_2 emissions if the total emission multipliers had changed and the final demand had not. In the same way, the second term on the RHS is the contribution of the change in the final demand to differences in CO_2 emissions assuming the total emission multipliers had remained constant.

The decomposition form in equation (5) can be further developed into a nested form (Dietzenbacher and Hoekstra, 2002). That is, the first term can be further decomposed into the underlying sources of the changes in the total emission coefficients $\boldsymbol{\mu}^c$. That is, recall that by definition, $\boldsymbol{\mu}^c = \mathbf{cL}$. Thus, the two polar decompositions of $\Delta\boldsymbol{\mu}^c$ are specified as follows.

$$\Delta\boldsymbol{\mu}^{c} = \Delta\mathbf{c}\cdot\mathbf{L}_0 + \mathbf{c}_1\cdot\Delta\mathbf{L} \tag{6a}$$

$$\Delta\boldsymbol{\mu}^{c} = \Delta\mathbf{c}\cdot\mathbf{L}_1 + \mathbf{c}_0\cdot\Delta\mathbf{L} \tag{6b}$$

Substituting the average of expressions (6a) and (6b) into equation (5) suggests that its first term $0.5\cdot\Delta\boldsymbol{\mu}^{c}(\mathbf{F}_0^{d}+\mathbf{F}_1^{d})\mathbf{i}$ can be decomposed further into the following two components.

$$0.25\cdot\Delta\mathbf{c}(\mathbf{L}_0+\mathbf{L}_1)(\mathbf{F}_0^{d}+\mathbf{F}_1^{d})\mathbf{i} \tag{7a}$$

$$0.25\cdot(\mathbf{c}_1+\mathbf{c}_0)\Delta\mathbf{L}(\mathbf{F}_0^{\mathbf{d}}+\mathbf{F}_1^{\mathbf{d}})\mathbf{i} \tag{7b}$$

To account for import substitution in an open economy, $\Delta\mathbf{L}$ can be further decomposed into the input mix, which indicates a sector's relative productivity (fewer intermediate inputs are used per unit of final demand) and import substitution, which identifies imports share inputs (Jacobsen, 2000). Based on equation (2), $\mathbf{A}_0^{d}=(1-\hat{\mathbf{R}}_0)\mathbf{A}_0$ and $\mathbf{A}_1^{\mathbf{d}}=(1-\hat{\mathbf{R}}_1)\mathbf{A}_1$, respectively, so that the decomposition of $\Delta\mathbf{L}$ can be expressed as:

$$\begin{aligned}
\Delta\mathbf{L} &= \mathbf{L}_1-\mathbf{L}_0\\
&=(\mathbf{I}-\mathbf{A}_1^{\mathbf{d}})^{-1}-(\mathbf{I}-\mathbf{A}_0^{\mathbf{d}})^{-1}\\
&=\{\mathbf{I}-[(\mathbf{I}-\hat{\mathbf{R}}_1)\mathbf{A}_1]\}^{-1}-\{\mathbf{I}-[(\mathbf{I}-\hat{\mathbf{R}}_0)\mathbf{A}_0]\}^{-1}\\
&=\left\langle\{\mathbf{I}-[(\mathbf{I}-\hat{\mathbf{R}}_1)\mathbf{A}_1]\}^{-1}-\{\mathbf{I}-[(\mathbf{I}-\hat{\mathbf{R}}_0)\mathbf{A}_1]\}^{-1}\right\rangle+\left\langle\{\mathbf{I}-[(\mathbf{I}-\hat{\mathbf{R}}_0)\mathbf{A}_1]\}^{-1}-\{\mathbf{I}-[(\mathbf{I}-\hat{\mathbf{R}}_0)\mathbf{A}_0]\}^{-1}\right\rangle\\
&=(\mathbf{L}_1-\mathbf{L}^{*})+(\mathbf{L}^{*}-\mathbf{L}_0)
\end{aligned}$$

or

$$\begin{aligned}
\Delta\mathbf{L} &= \mathbf{L}_1-\mathbf{L}_0\\
&=(\mathbf{I}-\mathbf{A}_1^{\mathbf{d}})^{-1}-(\mathbf{I}-\mathbf{A}_0^{\mathbf{d}})^{-1}\\
&=\{\mathbf{I}-[(\mathbf{I}-\hat{\mathbf{R}}_1)\mathbf{A}_1]\}^{-1}-\{\mathbf{I}-[(\mathbf{I}-\hat{\mathbf{R}}_0)\mathbf{A}_0]\}^{-1}\\
&=\left\langle\{\mathbf{I}-[(\mathbf{I}-\hat{\mathbf{R}}_1)\mathbf{A}_0]\}^{-1}-\{\mathbf{I}-[(\mathbf{I}-\hat{\mathbf{R}}_0)\mathbf{A}_0]\}^{-1}\right\rangle+\left\langle\{\mathbf{I}-[(\mathbf{I}-\hat{\mathbf{R}}_1)\mathbf{A}_1]\}^{-1}-\{\mathbf{I}-[(\mathbf{I}-\hat{\mathbf{R}}_1)\mathbf{A}_0]\}^{-1}\right\rangle\\
&=(\mathbf{L}^{\#}-\mathbf{L}_0)+(\mathbf{L}_1-\mathbf{L}^{\#})
\end{aligned}$$

where $\mathbf{L}^{*}=\{\mathbf{I}-[(\mathbf{I}-\hat{\mathbf{R}}_0)\mathbf{A}_1]\}^{-1}$ and $\mathbf{L}^{\#}=\{\mathbf{I}-[(\mathbf{I}-\hat{\mathbf{R}}_1)\mathbf{A}_0]\}^{-1}$, respectively.

Substituting the average of these two expressions into equation (7b), the first term

$0.5 \cdot \Delta\boldsymbol{\mu}^c(\mathbf{F}_0^d + \mathbf{F}_1^d)\mathbf{i}$ in equation (5) can be further decomposed into the following three components.

$$0.25 \cdot (\Delta\mathbf{c})(\mathbf{L}_0 + \mathbf{L}_1)(\mathbf{F}_0^{\mathbf{d}} + \mathbf{F}_1^{\mathbf{d}})\mathbf{i} \tag{8a}$$

$$0.125 \cdot (\mathbf{c}_1 + \mathbf{c}_0)[(\mathbf{L}^* - \mathbf{L}_0) + (\mathbf{L}_1 - \mathbf{L}^\#)](\mathbf{F}_0^{\mathbf{d}} + \mathbf{F}_1^{\mathbf{d}})\mathbf{i} \tag{8b}$$

$$0.125 \cdot (\mathbf{c}_1 + \mathbf{c}_0)[(\mathbf{L}_1 - \mathbf{L}^*) + (\mathbf{L}^\# - \mathbf{L}_0)](\mathbf{F}_0^{\mathbf{d}} + \mathbf{F}_1^{\mathbf{d}})\mathbf{i} \tag{8c}$$

Equation (8a) is the emission coefficient component, i.e., the change in CO_2 emissions due to the changes in the energy structure, energy combustion efficiency and energy consumption efficiency. The first input mix component in equation (8b) shows how changes in input intensity affect CO_2 emissions. The second input mix component in equation (8c) shows how the share of imports in intermediate inputs affects CO_2 emissions.

Domestic final demand $\mathbf{F}^d$ also can be further subdivided into three factors: **B** is the $n \times 3$ final use product structure matrix whose element b_{ik} represent the share of the final product from sector *i* in the final demand of product category k, $\hat{\mathbf{S}}$ is a 3×3 diagonal matrix with the vector of final demand shares for each of the three final demand sectors, *k*. The shares sum to 1.0. The total level of domestically fulfilled final demand is given by the scalar *F*, such that $\mathbf{F}^d = F\mathbf{B}\hat{\mathbf{S}}$. The two polar decompositions of $\Delta\mathbf{F}^d$ are.

$$\Delta\mathbf{F}^{\mathbf{d}} = \Delta F\mathbf{B_0}\hat{\mathbf{S}}_{\mathbf{0}} + F_1\Delta\mathbf{B}\hat{\mathbf{S}}_{\mathbf{0}} + F_1\mathbf{B_1}\Delta\hat{\mathbf{S}}$$

$$\Delta\mathbf{F}^{\mathbf{d}} = \Delta F\mathbf{B_1}\hat{\mathbf{S}}_{\mathbf{1}} + F_0\Delta\mathbf{B}\hat{\mathbf{S}}_{\mathbf{1}} + F_0\mathbf{B_0}\Delta\hat{\mathbf{S}}$$

Substituting the average of these two expressions into equation (5) implies that its second term $0.5 \cdot (\boldsymbol{\mu}_0^{\mathbf{c}} + \boldsymbol{\mu}_1^{\mathbf{c}})\Delta\mathbf{F}^{\mathbf{d}}\mathbf{i}$ can be decomposed further into the following three components.

$$0.25\cdot(\boldsymbol{\mu}_0^c+\boldsymbol{\mu}_1^c)\Delta F(\mathbf{B}_0\hat{\mathbf{S}}_0+\mathbf{B}_1\hat{\mathbf{S}}_1)\mathbf{i} \tag{8d}$$

$$0.25\cdot(\boldsymbol{\mu}_0^c+\boldsymbol{\mu}_1^c)(F_1\Delta\mathbf{B}\hat{\mathbf{S}}_0+F_0\Delta\mathbf{B}\hat{\mathbf{S}}_1)\mathbf{i} \tag{8e}$$

$$0.25\cdot(\boldsymbol{\mu}_0^c+\boldsymbol{\mu}_1^c)(F_1\mathbf{B}_1+F_0\mathbf{B}_0)\Delta\hat{\mathbf{S}}\mathbf{i} \tag{8f}$$

Equation (8d) in the level component, i.e., it yields amount of change in CO_2 emissions due to the change in the level of the final demand. The final demand shifts component in expression (8e) shows how shifts in final demand shares across the three final demand sectors affects CO_2 emissions. The consumption function component in equation (8f) yields the size of the effects on CO_2 emissions due to changes in the shares of commodities and services used by each of the three final demand sectors.

2.2 Forward and backward linkages

Following Lenzen (2003), each sector's total polluting character is identified using intersectoral linkages of CO_2 emissions. This approach identifies those sectors that have the most potential to reduce emissions via small changes in economic activity. Standard multipliers are used as the criteria in this paper.

The backward linkage measure is that from the Leontief inverse $\mathbf{L}=(\mathbf{I}-\mathbf{A}^d)^{-1}$, which is heavily used in empirical studies. Rasmussen (1956) noted that the element l_{ij} of **L** represents the increase of output in industry *i* due to a unit increase of final demand in industry *j*. Then, the sum of the elements in the j^{th} column of the Leontief inverse matrix

$$\mu_j=\sum_{i=1}^{n} l_{ij} \tag{9}$$

measures the total output from all sectors generated from one unit of final demand of sector $j's$ output. Thus, μ_j reflects the backward linkage of sector j. Similarly, element $\sum_{i=1}^{n} c_i l_{ij}$ of $\boldsymbol{\mu}^c$ is the total of CO_2 emissions in the economy necessary to satisfy a unit of final demand produced by sector j.

The use of the corresponding row sums of Leontief inverse that were suggested by Rasmussen (1956) as indicators for forward linkages has been criticized (Cella, 1984). Instead, the Ghosh inverse $\mathbf{G} = (\mathbf{I} - \mathbf{B}^d)^{-1}$ [1]was suggested as a possible alternative for measuring forward linkages (Augustinovics, 1970; Beyers, 1976; Jones, 1976; Dietzenbacher, 1992; Miller and Lahr, 2001). Here, element g_{ij} of matrix **G** identifies the increase in the output of industry j due to a unit increase of the primary inputs in industry i. Thus, the sum of the elements in the i^{th} row of the Ghosh inverse matrix

$$\vec{\mu}_i = \sum_{j=1}^{n} g_{ij} \qquad (10)$$

gives the effect on the total output throughout all sectors of a unit change in primary inputs for sector i. Therefore, $\vec{\mu}_i$ reflects some measure of forward linkages for sector i.[2] Likewise[3], element $\sum_{j=1}^{n} g_{ij} c_j$ of $\vec{\boldsymbol{\mu}}^c$ can be interpreted as the subtotal of CO_2 emissions in the economy necessary to utilise a unit of primary inputs in sector i.

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[1] $\mathbf{B}^\mathbf{d}$ is the $n \times n$ matrix of domestic output coefficients and usually be defined as $\mathbf{B}^d = \{B_{ij}^d\} = \{x_{ij}^d / x_i\}$, where x_{ij}^d stands for the domestically supplied inputs.

[2] Following on concerns by Oosterhaven (1988, 1996) about the plausibility of the Ghosh inverse in measuring supply-side issues, Dietzenbacher (1997) noted that if it is reinterpreted as a price model, albeit in Leontief fashion, it remained valid. The catch, however, is that in this interpretation sectoral output values change as a function of price changes introduced as changes in value added. That is, multipliers of the Leontief price model, as he called this re-interpretation of the Ghosh model, report how external price changes (and not quantity changes as in the conventional Leontief model) diffuse through the value of production in a Leontief system.

[3] When considering the impact of CO_2 emissions, the standard Ghosh model (Ghosh, 1958) can be generalised as: $\vec{C} = \mathbf{x}\mathbf{c}' = \mathbf{v}(\mathbf{I} - \mathbf{B}^d)^{-1}\mathbf{c}' = \mathbf{v}\vec{\boldsymbol{\mu}}^c$, where **v** is the vector of value added by industry.

The analysis of “key sectors” is a useful approach for characterising the impacts of sectors. Following Rasmussen (1956), one can normalise the backward and forward linkage measures according to the overall measure of the economy as a whole. Then, the key emission sectors can be identified through the generalised forward and backward linkages using the following equations.

$$BL_j^c = \frac{\mu_j^c}{(\mathbf{i}'\boldsymbol{\mu}^c)/n} \tag{11}$$

$$FL_i^c = \frac{\vec{\mu}_i^c}{(\mathbf{i}'\vec{\boldsymbol{\mu}}^c)/n} \tag{12}$$

The concept of key sectors as described by Hirschman (1958) can be readily transferred to emission linkages. In this case $BL_j^c > 1$ suggests that a unit increase in the final demand of sector j will produce an above-average increase in CO_2 emissions, and $FL_i^c > 1$ suggests that a unit increase in the primary input of sector i will create an above-average increase in CO_2 emissions. A sector can clearly be defined as a key CO_2 emission sector if both $BL^c > 1$ and $FL^c > 1$. By definition, initial small changes in key emission sectors are expected to transmit above-average emission linkages. That is, they accelerate and amplify the total CO_2 emissions in the economy as a whole. It is evident that key emission sectors play a decisive role in production structure changes in terms of CO_2 emission control.

To depict the production structure of an economy from the emission linkage point of view, a composite indicator is defined as follows:

$$\omega = \frac{\mathbf{i}_o'\mathbf{F}^d\mathbf{i}}{\mathbf{i}'\mathbf{F}^d\mathbf{i}} \tag{13}$$

where ω is the share of final demand in GDP for the key emission sectors, $\mathbf{i}_o$ is a vector of dimension n in which the p^{th} element is 1 (unity) and all others are 0 (zero), and p is the economy's key emission sector. This, the greater the value of ω, the more important is the key emissions sector to the production structure of the economy.

3. CASE STUDY

3.1 Data sources and preconditioning

More recently, several studies (see for example, Baiocchi and Minx, 2010; Arto and Dietzenbacher, 2014; Xu and Dietzenbacher, 2014) have applied SDA approach within an international multiregional input-output (MRIO) framework to identify drivers of the growth in global greenhouse gas emissions from a consumption-based perspective. In that case, both producers abroad and at home are of concern, hence information on the emission intensity and production structure in global supply chains of the imports is needed from MRIO.

In contrast with above SDA literature, however, the present study focuses on China's production-source CO_2 emissions. The problem addressed here is the relative contribution of a set of factors that is expected to influence China's CO_2 emissions in its production. Therefore, from a national production-based perspective, the current SDA was performed within a single regional input-output (SRIO) framework and the import substitution effect was investigated by assuming that imported products are produced in the same way as they are domestically.

The 2005 and 2010 Chinese IO tables were obtained from the official website of Chinese Input-Output Association (www.iochina.org.cn), covering 42 sectors respectively, which are not identical with the energy consumption data sourced from the *China Energy Statistical Yearbook* (NBS, 2008; 2011). Therefore, to comply with relevant data on energy statistics, both IO tables were aggregated to 28 sectors (see

Appendix A). Meanwhile, because decomposition studies require economic data in constant prices, the 2010 IO table was adjusted to 2005 constant prices. Following Liu and Peng (2010), this paper uses an agricultural product price index for agriculture (sector 1), the installed price index for construction works for construction (sector 25), value added index for transport and warehousing (sector 26) and service activities (sector 28) and retail price index for wholesale and retail trade (sector 27). For the mining and manufacturing sectors (sector 2 through sector 24) producer price index was used. Deflators were compiled based on the price data provided from various years of the *China Statistical Yearbook*.

In the absence of comprehensive data on emissions per sector, studies on China's CO_2 emissions have traditionally estimated the sectoral emissions based on some reasonable approximations. In line with the common practice, CO_2 emission coefficients by fuel were calculated by using the IPCC (2006) reference approach, and sectoral emissions were estimated for each sector from the nine types of energy that could possibly be used (Coal, Coke, Crude oil, Gasoline, Kerosene, Diesel Oil, Fuel Oil, Natural Gas and Electricity) (see Appendix B for details on the calculations).

3.2 Results and discussions

3. 2.1 Sources of changes in CO_2 emissions

In the five years from 2005 to 2010, China's production-source CO_2 emissions increased by 41% (from 4,628 to 6,571 Mtonnes). According to equations (8a)-(8f), a summary of the proximate causes of change in China's production-source CO_2 emissions is presented in Figure 1. At the national level, trends in emissions intensity and input intensity decreased CO_2 emissions. The change in emission intensity was the dominant factor in this group, decreasing CO_2 emissions by 37.5% (a drop of

1,737 Mtonnes) over the period. Meanwhile, the change in the input intensity caused only a relatively small decrease in CO_2 emissions of 0.5% (26 Mtonnes). This suggests that efforts to improve production efficiency were not the success the central government might have hoped they had been, at least in reducing emissions. In contrast, trends in the imports of intermediate goods, final demand level, final demand sector shares and final demand consumption functions have effectively elevated CO_2 emissions. Rising final demand levels was a prime culprit; It caused CO_2 emissions to rise by 62.4% (2,889 Mtonnes). The change in imports was the second most important proximate cause of a rise in CO_2 emissions; they increased the CO_2 emissions by 9.3% (432 Mtonnes) over the study timeframe. This, of course, implies that China was reducing its imports and building an economy to meet its surging domestic market. Indeed, the contribution of the decrease in imports to CO_2 emissions outstripped the emission savings gained from trends in input intensity, so that in net production structure components enable CO_2 emissions growth of 8.8% (406 Mtonnes).

These findings are consistent with Guan et al. (2009) and Minx et al. (2011), but they provide richer detail pertinent to crafting CO_2 mitigation policies. In addition, the change in sectoral shares of final demand and change in the consumption functions enabled, respectively, rises in CO_2 emissions of 3.8% (176 Mtonnes) and 3.4% (156 Mtonnes). Clearly all aspects of final demand during the period were counter-productive in alleviating China’s emissions problem.

[Figure 1 here]

Final demand was examined more closely for policy purposes. Figure 2 is a graphical representation of the SDA results by the three final demand sectors for the period of 2005-2010. It shows that rises in final demand pushed CO_2 emissions upwardly. During the period, of the 64% growth in CO_2 emissions attributed to the total final demand level, 26.7% (1,234 Mtonnes) is attributable to growth in capital investment, 18% (833 Mtonnes) is due to rises in exports and 17.7% (822 Mtonnes) is due to growth in consumption. From the above it is clear that, of the three final demand sectors, the share of final demand allocated to capital investment grew most rapidly, this shift is associated a 2.9% (133 Mtonnes) increase in CO_2 emissions—the largest for the three sectors, consumption follows with 0.6% (29 Mtonnes), and exports at 0.3% (15 Mtonnes).

The dominance of capital investment as a cause of rising CO_2 emissions through 2007 is fairly well established in the literature (c.f., Guan et al., 2009; Minx et al., 2011). This was a period of build-up leading up to and past the 2008 Olympics in Beijing, after all. But, as Minx et al. (2011) note, capital investment also enables changes in production structure. Moreover, as Zhang and Lahr (2014) note, capital investment has a very energy-intensive (and, hence, emissions-intensive) supply chain, using higher-than-normal industry shares of iron and steel, cement and electricity. The upside of this is that the new construction should have a longer lifecycle than the infrastructure that it replaced, making it in net a greener use.

Although the overall effect of the changes in final demand composition on CO_2 emissions is unfavourable, the effects of different categories varied significantly: capital investment increased CO_2 emissions by 13.6% (632 Mtonnes), whereas consumption and exports respectively decreased CO_2 emissions by 7.1% (-332 Mtonnes) and 3.1% (-145 Mtonnes). This finding implies that some small amount of greening transpired in China's consumption and exports.

[Figure 2 here]

Meanwhile, a further decomposition was performed on the sector level to gain some detailed information on the sources of the changes in China's CO_2 emissions. Table 1 presents the SDA results of changes in CO_2 emissions by sector for the period between 2005 and 2010.

[Table 1 here]

The decomposition results by sector in Table 1 show some clear trends regarding the changes in CO_2 emissions due to emission intensity, import substitution and final demand level changes. First, most sectors developed cleaner technologies as shown by their lower emission intensity; still, a few sectors increased their emission intensity: Transport and warehousing (Sector 26), Wholesale and retail trade (Sector 27) and Service activities (Sector 28). A possible explanation may be that the central government largely focussed its emission reduction polices on manufacturing sectors, and monitored nonmanufacturing sectors less closely. Second, on average, the effects of import substitution on CO_2 emissions were fairly consistent across sectors and, with the exception of petroleum and natural gas extraction (Sector 3), tended to place upward pressure on CO_2 emissions. The implication is that a policies encouraging import substitution are effective, but adversely affect CO_2 levels. Finally, final demand growth is strong and contributes most to the overall rise in emissions across sectors during the observed period. This too is consistent with the results of previous analyses of the economy as a whole, as reported earlier.

3.2.2 Accounting for CO_2 emissions from emission linkages

[Table 2 here]

We now consider the carbon reduction from a different perspective. We want to know which sectors have the greatest potential to reduce China's CO_2 levels. An alternative way of looking at this is to find out which contribute most to CO_2 levels. For if all sectors can produce in a greener fashion, then those that pollute most should be rewarded with closer scrutiny. Table 2 presents an overview of the forward and backward linkages by sector with respect to CO_2 emissions. Following the discussion in the previous section, a total of 10 sectors, including the Coal mining and dressing (Sector 2), Metal ore mining (Sector 4), Petroleum processing, coking and nuclear fuel processing (Sector 11), Chemical products related industry (Sector 12), Non-metal mineral products (Sector 13), Metal smelting and pressing (Sector 14), Production and supply of electricity and heating power (Sector 22), Gas production and supply (Sector 23), Water production and supply (Sector 24), and Transport and warehousing (Sector 26) were identified as "key emission sectors" in China economy in 2005. By 2010, only Gas production and supply (Sector 23) dropped off of the list. Moreover, with the exception of Water production and supply, all of these are sectors one would intuitively select as major polluting sectors since they all use significant shares of energy resources.

These polluting sectors can play a critical role in helping China reduce its carbon levels since they have above-average emission linkages; That is, relatively small changes within these key emission sectors could affect the total CO_2 emissions in an economy in a major way. Note, however, the production structure of the Chinese economy was more CO_2-intensive in 2010 than it was in 2005, as the GDP share of key emission sectors ω increased from 0.29 to 0.30.

To gain a deeper understanding of the structure changes in terms of CO_2 emissions, the key emission sector shares for the intermediate input and final demand are shown side by side in Figure 3. Compared to 2005, intermediate inputs comprise more key emission sector products in 2010. In addition, the suspected rising share of domestic inputs is readily identified. Indeed, in net, more intermediate products from key emission sectors are produced domestically by China when compared to the content of imports from abroad. This of course, further stimulates CO_2 emissions in China.

Meanwhile, final demand required less production from key emissions sector in 2010 than in 2005. A closer look at each category of final demand leads to several interesting conclusions. First, exports had the highest shares of key emission sectors in both 2005 and 2010, which implies that key emission sectors manufacture more products for export than for domestic consumption and investment. Second, compared to the structure in 2005, consumption and exports used less production from key emission sectors while capital investment used more in 2010.

This detailed information on changes in the final demand composition provides a bridge between the effect of final demand sector shares and the consumption functions of final demand on CO_2 emissions. That is, because shares of consumption and exports lowered and because both decreased their requirements for the production of key emission sector shares, emissions were able to grow substantially from 2005 to 2010.

[Figure 3 here]

4. CONCLUSION

Because it is the world's biggest polluter and still developing economically, China must keep abreast of international trends in CO_2 reduction. It needs well-founded information on most effective mitigation policies. This paper provides a structural decomposition analysis and a linkage analysis to examine the origins of China's recent growing CO_2 emissions identifying both key contributing factors and sectors. The main findings and policy implications can be summarized below.

First, on a national level, China's recent efforts to reduce emission intensity have proven effective in mitigating the CO_2 emissions. Thus, the central government should continue to support technological improvements that achieve energy savings. The government promise to move toward the greater use of renewable energy resources in producing electricity will help significantly in this regard. Moreover, as pointed out by Zhang and Lahr (2014) a more efficient market for heating and electricity will help as well. But, observed rises emissions intensity in nonmanufacturing sectors suggest the central government needs to start paying more attention to the economy beyond manufacturing to reduce carbon emissions.

Second, a significant amount of CO_2 emission growth appears to have emanated from final demand. This means that CO_2 emissions can be adjusted by altering the pattern of demand in China. Thus the central government should pay more attention CO_2-based lifecycle costs of its investments as well as providing incentives to reign in consumer lifestyles so that final demand becomes more sustainable. That is, it should encourage reductions in material consumption in the long-run and shifts toward less material-intensive consumption in general. Detailed information for final demand categories suggest domestic investments explain much of the recent increases in China's CO_2 emissions. But both SDA and emission linkage analysis indicate that CO_2 emissions from capital investment in China may be a serious challenge since it is intertwined long-run changes in the national's production structure. Still, a clear message is that domestic investment should be designed carefully to achieve long-run CO_2 efficiency improvements both by assuring a longer effective life for China's new infrastructure as well as in assuring that the nation's production systems are shifted away from CO_2 intensive industries when and where possible.

Third, during the observed time period, the decrease in input intensity caused only a relatively small reduction in CO_2 emissions; still, import substitution effective increased China’s capacity to produce CO_2 emissions. This is a key finding that is unique to our research due to our approach. This suggest that while it is important for China to build its economy, it should consider doing so in a more selective way that minimizes further CO_2 rises. It is evident that encouraging more imported intermediates from trade partners with the capacity to produce products in a greener manner would be a good way to mitigate CO_2 in China’s as well as globally.

Also, we identified several sectors that were the key CO_2 emitters in 2005 and 2010. China should target mitigation efforts on these sectors as well as on final demand. With this in mind, designing a GDP share cap for these key emission sectors within the economy could reasonable strategy for the Chinese government.

In summary a main finding of this paper is that China should pay attention to its trade policies because the recent changes in its trade structure have been counter-productive in terms of CO_2 emission control. That is, it is crucial that China take efforts to try to optimize the composition of its imports and exports via improved technology and environmental thresholds and to minimize any adverse effects that should emanate from the displacement of domestic industries that have high content of CO_2 embodied in the international trade.

Note that we did not address the difference in emission intensities between domestic and foreign production in this paper. If changes in trade policies as proposed here are deemed reasonable, then a closer examination of the emission intensities of imports to China is sorely needed. This suggests that an SDA in an international MRIO framework needs a topic of future research.

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Appendix A

Table A1 Comparison of Sector Classification

42 sectors in IO table	28 aggregated Sectors
1 Agriculture	1 Agriculture
2 Coal mining and dressing	2 Coal mining and dressing
3 Petroleum and natural gas extraction	3 Petroleum and natural gas extraction
4 Metal ore mining	4 Metal ore mining
5 Non-ferrous mineral mining	5 Non-ferrous mineral mining
6 Manufacture of food products and tobacco processing	6 Manufacture of food products and tobacco processing
7 Textile	7 Textile
8 Wearing apparel, leather, furs and related products	8 Wearing apparel, leather, furs and related products
9 Sawmills and furniture	9 Sawmills and furniture
10 Paper and paper products, printing and reproduction	10 Paper and paper products, printing and reproduction
11 Petroleum processing, coking and nuclear fuel processing	11 Petroleum processing, coking and nuclear fuel processing
12 Chemical products related industry	12 Chemical products related industry
13 Non-metal mineral products	13 Non-metal mineral products
14 Metal smelting and pressing	14 Metal smelting and pressing
15 Metal products	15 Metal products
16 Common and special equipment	16 Common and special equipment
17 Transportation equipment	17 Transportation equipment
18 Electric equipment and machinery	18 Electric equipment and machinery
19 Telecommunications equipment, computer and other electronic equipment	19 Telecommunications equipment, computer and other electronic equipment
20 Instruments, meters, cultural and office machinery	20 Instruments, meters, cultural and office machinery
21 Other manufacturing products	21 Other manufacturing products
22 Recycling and disposal of waste	
23 Production and supply of electricity and heating power	22 Production and supply of electricity and heating power
24 Gas production and supply	23 Gas production and supply
25 Water production and supply	24 Water production and supply
26 Construction	25 Construction
27 Transport and warehousing	26 Transport and warehousing
30 Wholesale and retail trade	27 Wholesale and retail trade
28 Postal	28 Service activities
29 Information transferring, computer service and software trade	
31 Hotels and Restaurants	
32 Finance and Insurance	

33 Real Estate	
34 Rent and business activities	
35 Scientific research institutions	
36 Technological services and geological prospecting	
37 Water, environment and public facilities management	
38 Residents service and other service trades	
39 Education	
40 Health care, social security and social welfare	
41 Culture, sports and entertainment	
42 Public administration and social organizations	

Appendix B

More specifically, the sectoral CO_2 emissions from fossil fuel combustion, denoted as C_i, can be calculated using the formula:

$$C_i = \sum_{\tau=1}^{m} (FC_\tau \times EF_\tau \times EC_\tau)$$

where FC_τ is the heat value of the τth type of fuel used in production, in units of terajoule (TJ); EF_τ is the emission factor of the τth type of fuel, in units of tCO_2/TJ; EC_τ is the consumption of the τth type of fuel, m represents the number of total types of fuel used in production of sector i.

Table 1

SDA of changes in China’s CO_2 emissions between 2005 and 2010 at sector level, Mtonnes

Sector	Emission intensity	Inputs intensity	Import substitution	Final demand Level	Final demand allocation	Final demand composition
1 Agriculture	-13	-28	1	69	-16	-9
2 Coal mining and dressing	-48	-28	5	107	50	0
3 Petroleum and natural gas extraction	-27	15	-14	47	-8	1
4 Metal ore mining	-24	15	5	25	-8	5
5 Non-ferrous mineral mining	-13	-3	3	13	2	2
6 Manufacture of food products and tobacco processing	-75	28	1	55	14	-13
7 Textiles	-58	14	10	63	1	-11
8 Wearing apparel, leather, furs and related products	-9	4	0	11	0	-2
9 Sawmills and furniture	-12	3	1	12	4	0
10 Paper and paper products, printing and reproduction	-47	14	7	49	-6	-5
11 Petroleum processing, coking and nuclear fuel processing	-25	-62	85	165	-42	5
12 Chemical products related industry	-399	54	82	384	87	-22
13 Non-metal mineral products	-311	72	16	278	16	77
14 Metal smelting and pressing	-466	-71	135	685	157	111
15 Metal products	-19	5	6	34	3	2
16 Common and special equipment	-51	18	5	51	-1	13
17 Transportation equipment	-40	10	1	33	28	6
18 Electric equipment and machinery	-14	0	3	19	9	1
19 Telecommunications equipment, computer and other electronic equipment	-13	2	5	26	6	-1
20 Instruments, meters, cultural and office machinery	-1	0	1	4	-3	0
21 Other manufacturing products	-26	6	0	19	9	0
22 Production and supply of electricity and heating power	-152	26	27	231	25	3
23 Gas production and supply	-14	4	1	7	4	-1
24 Water production and supply	-1	-9	1	9	7	-1
25 Construction	-20	-1	0	50	2	23
26 Transport and warehousing	48	-48	36	254	-107	-1
27 Wholesale and retail trade	21	-23	5	64	-20	-6
28 Service activities	71	-44	5	124	-36	-23
Total	**-1737**	**-26**	**432**	**2889**	**176**	**156**

Table 2

Basic linkage features of CO_2 emissions per sector

Sector	2005		2010	
	BL	**FL**	**BL**	**FL**
1 Agriculture	0.392	0.257	0.474	0.345
2 Coal mining and dressing	1.376	3.398	1.598	3.592
3 Petroleum and natural gas extraction	0.792	1.980	1.003	2.096
4 Metal ore mining	1.041	1.269	1.084	1.205
5 Non-ferrous mineral mining	0.999	1.055	0.999	0.917
6 Manufacture of food products and tobacco processing	0.522	0.244	0.484	0.186
7 Textile	0.844	0.539	0.786	0.508
8 Wearing apparel, leather, furs and related products	0.578	0.076	0.586	0.080
9 Sawmills and furniture	0.718	0.249	0.697	0.208
10 Paper and paper products, printing and reproduction	0.938	0.742	0.858	0.664
11 Petroleum processing, coking and nuclear fuel processing	1.387	2.274	1.604	3.126
12 Chemical products related industry	1.339	1.656	1.186	1.319
13 Non-metal mineral products	1.860	2.326	1.686	1.851
14 Metal smelting and pressing	2.223	3.569	2.103	3.241
15 Metal products	1.298	0.402	1.208	0.433
16 Common and special equipment	1.028	0.195	0.898	0.175
17 Transportation equipment	0.917	0.179	0.727	0.119
18 Electric equipment and machinery	1.005	0.121	1.000	0.099
19 Telecommunications equipment, computer and other electronic equipment	0.612	0.072	0.469	0.072
20 Instruments, meters, cultural and office machinery	0.730	0.066	0.572	0.097
21 Other manufacturing products	0.704	0.535	0.611	0.329
22 Production and supply of electricity and heating power	1.311	2.080	1.414	2.233
23 Gas production and supply	1.473	1.381	0.913	0.856
24 Water production and supply	1.121	1.526	1.335	1.419
25 Construction	0.924	0.065	1.032	0.065
26 Transport and warehousing	1.053	1.365	1.480	2.149
27 Wholesale and retail trade	0.381	0.247	0.552	0.382
28 Service activities	0.435	0.134	0.642	0.232
Key emission sector ratio ω	**0.29**		**0.30**	

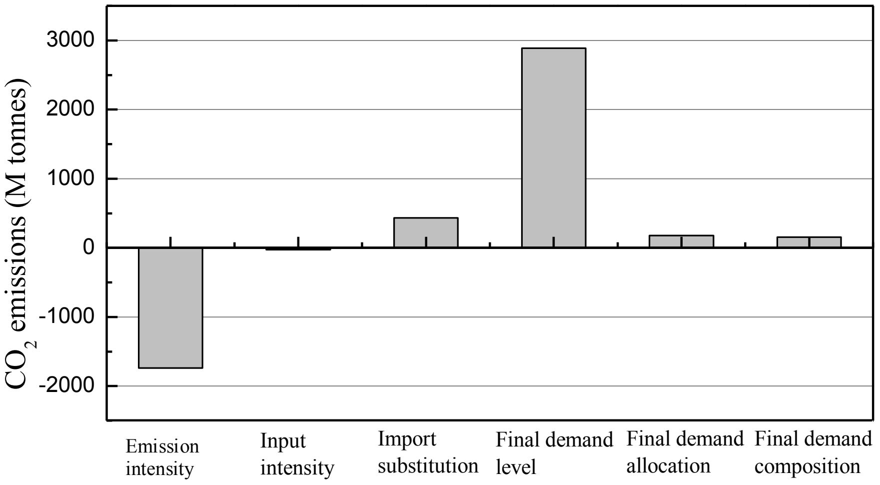

Fig. 1 SDA of changes in China's CO_2 emissions between 2005 and 2010: national level

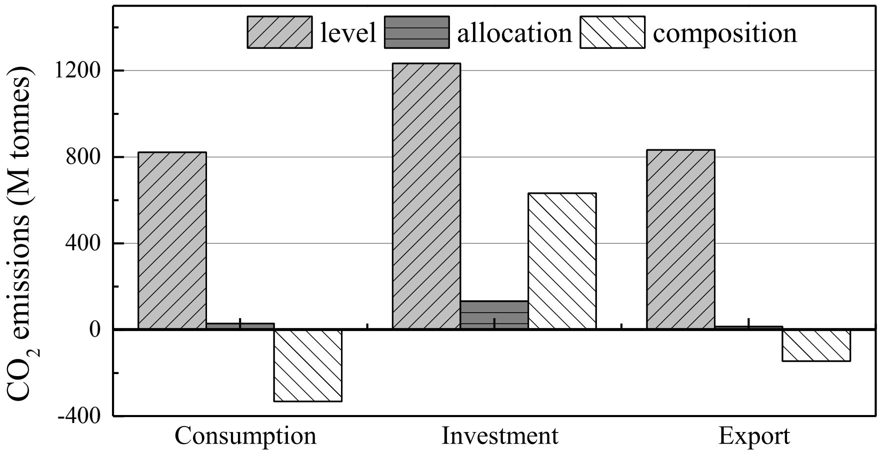

Fig. 2 SDA of changes in China's CO_2 emissions between 2005 and 2010: final demand category

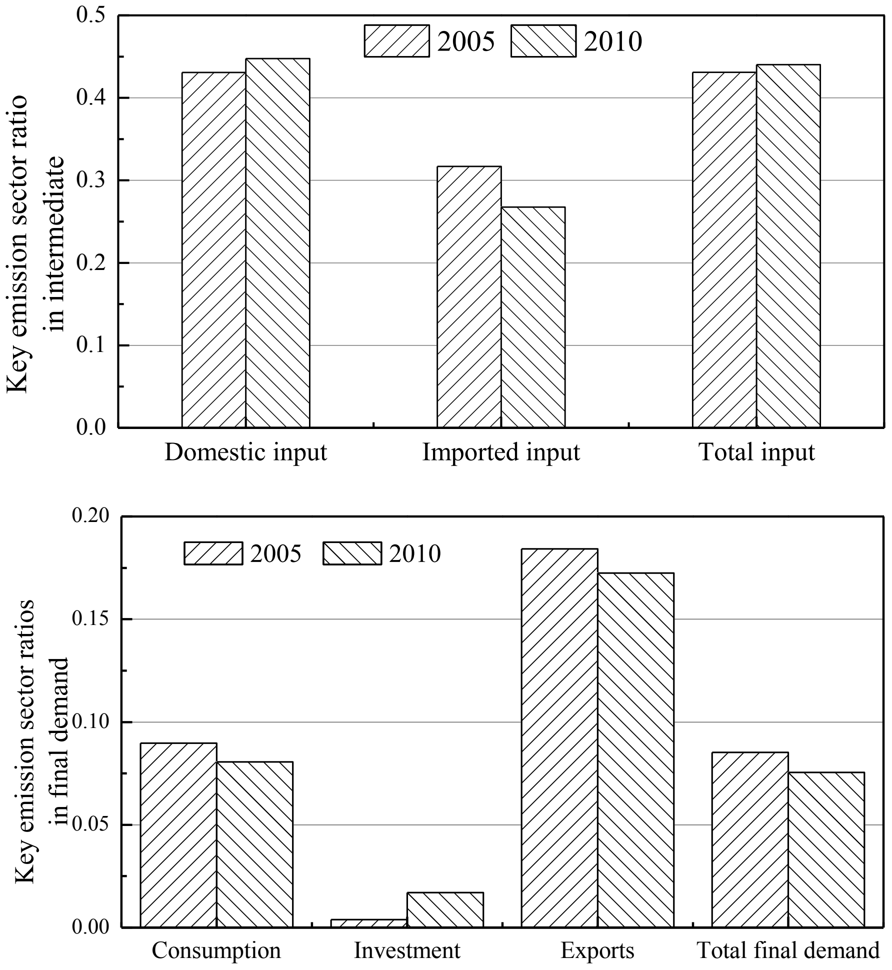

Fig. 3 Key emission sector ratios in the intermediate and final demand: 2005 vs. 2010