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Analysis

# The Impact on Global Greenhouse Gas Emissions of Geographic Shifts in Global Supply Chains

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ABSTRACT

During the past two decades there has been a shift in the geography of Global Supply Chains (GSCs) from developed countries to China, and more recently from China to successor developing countries in South Asia, Africa and Latin America. The shift in GSC geography influences global greenhouse gas (GHG) emissions because of an energy efficiency and low-carbon technology gap between developed and developing economies. Our simulations indicate that changing GSC geography toward China positively contributed, on average (2001–2008), 919 Mt $CO_2$ equivalents to global GHG emissions annually. In addition, there are potentially even larger indirect effects, including import-related and transportation-related emissions that are attributable to GSC shift-related improvements in developing world consumption and infrastructure. We then investigate the emission impact of a further GSCs shift toward South Asia, Africa and Latin America. Although the *direct* impact of such a shift is likely negative due to a lower dependency on coal as well as lower carbon intensities in South Asia, Africa and Latin America relative to China, it is likely that the direct effects are more than offset by the *indirect* shift-related effects associated with improvements in consumption and infrastructure. Our results have policy implications for future climate change mitigation.

## 1. Introduction

The last few decades have witnessed an increasing international fragmentation of production accompanied by important shifts in the geography of global supply chains (GSCs). GSCs are production-related processes in which the consumption of one country is met by production that takes place in many other countries. In these cases, different stages of productions are often linked through international trade. Lehmann (2012) summarizes the shifts beginning with the industrial revolution in Britain, after which the center of global production and trade shifted to Western Europe (especially Germany), then to the U.S., and two decades after World War II to Japan, Asia's Four Tigers (especially South Korea and Taiwan), and then to China. In a relatively short period of time China became the world's largest exporter of manufactured goods, and the label "Made in China" has become globally ubiquitous.

While China has benefited considerably from the changing geography of GSCs, in both gross trade volume and value-added terms (see, e.g. JETRO and WTO, 2011; OECD, WTO, and UNCTAD, 2013; Timmer et al., 2014), one consequence is its contribution to the huge rise in China's territorial greenhouse gases (GHG) emissions. According to BP statistics (2016), global $CO_2$ emissions increased by 12.80 gigatonnes (Gt) in 1990–2014 (i.e. from 22.70 Gt to 35.49 Gt), of which China contributed 7.30 Gt $CO_2$, or 57.1% of the increase (i.e. from 2.46 Gt to 9.76 Gt). The implied challenge to keeping global average surface temperatures from rising to 2 degrees above pre-industrial levels is obvious.

Although a substantial literature has demonstrated that international trade may account for 20%–30% of China's $CO_2$ emissions growth in recent decades (see, e.g. Yan and Yang, 2010; Liu and Ma, 2011; Weitzel and Ma, 2014; Jiang et al., 2015), China's high dependency on coal as primary energy input is one of the major reasons of its large increase $CO_2$ emissions (see, e.g. Fan et al., 2007; Guan et al., 2008; Zhang and Cheng, 2009). As of 2014, the ratio of coal in China's total primary energy consumption was 66.0%, while the average for the rest of the world (i.e world excluding China) was only 15.6%.[i] According to the German Wind Energy Association,[ii] each kilowatt hour (kWh) generated from wind power and natural gas emitted only 24 and 377 g of $CO_2$ in 2014, while each kWh generated from hard coal, and brown coal emitted 810, and 1000 g of $CO_2$, respectively.

The factors governing global GHG emissions growth, and the role of China in that growth have been extensively studied in production terms

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[i] Data is taken from BP statistics.

[ii] www.wind-energie.de.

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(see, e.g. Raupach et al., 2007; Canadell et al., 2007) and in consumption terms (see, e.g. Peters et al., 2012; Arto and Dietzenbacher, 2014, Kanemoto et al., 2014; Hoekstra et al., 2016; Malik et al., 2016; Malik and Lan, 2016). Arto and Dietzenbacher (2014) and Malik et al. (2016), for example, decomposed the global GHG emissions growth over time, while Hoekstra et al. (2016) and Malik and Lan (2016) focus on the role of changing pattern of international trade in global GHG emissions growth. Those studies based on structural or index decomposition mainly employed historical data and are concerned with temporal change. By decomposing China's emissions growth, they reflect to what extent increasing world demand for China's products as well as the change in international trade patterns (understood as the effect of China's integration into GVC) led to the growth of China's emissions for the period $t_0 - t_1$, and to what extent the decreasing carbon intensity (understood as the effects of technology upgrading of China) led to the reduction of China's emissions for the same period.But these studies barely address the energy efficiency and carbon-free technology gaps among countries.

Given the inter-country gap in energy efficiency and the ratio of fossil fuel to all primary energy inputs, it is natural to ask to what extent global GHG emissions growth is attributable to the change in the geography of GSCs from developed countries (with higher energy efficiencies and somewhat greater reliance on clean energies) to China (with lower energy efficiencies and much greater reliance on coal). By assuming that the global demand for goods remains unchanged in the absence of the GSC shift to China, the paper simulates the extent to which global emissions would have been lower. More specifically, we simulate global GHG emissions on the assumption that GSC-related productions of goods for export are replaced by those of other countries. Then we compare the findings from this thought experiment with the actual GHG emissions as a means of quantifying the direct effect of geographic shift of GSCs to China.

There is potentially an even larger indirect effect attributable to the GSC shift. In the past few decades, infrastructure-related GHG emissions in China are at least partly attributable to the shift in the locus of GSCs. Among other things, infrastructure construction is especially energy-intensive, and by extension carbon-intensive, when viewed on a life cycle basis, because it requires large quantities of energy-intensive steel and cement inputs (Perz, 2014). These are largely submerged in formal analyses of global emission growth because most of the literature combines household and government consumption along with fixed capital formation into a single consumption bundle (see, e.g. Raupach et al., 2007; Canadell et al., 2007; Peters et al., 2012; Arto and Dietzenbacher, 2014). In addition, there are also increased import and international transport- related GHG emissions, as well as increased emissions from consumption growth in China, that are attributable to the shift of GSCs to China. In the absence of the GSC shift these indirectly-related GHG emissions would not have occurred.

Furthermore, with increasing labor and land costs in China, there are signs that the center of GSC operations is beginning to move from China to less developed countries in South Asia and Africa (see, e.g. Lehmann, 2012; Stratfor, 2013; AfDB, OECD and UNDP, 2014). These countries, on the whole, have low energy efficiencies and a less developed infrastructure than does China, so that a further shift in GSCs may result in additional GHG emissions. This point can be understood by noting that infrastructure (e.g. road, rail and power plants) and manufacturing efficiencies in these countries are below those of China, making them less efficient as centers of GSC production (AfDB, OECD and UNDP, 2014). It is also interesting to investigate how a shift in GSC location from China to other developing countries would influence global GHG emissions.

Our paper is organized as follows. In Section 2 we introduce our methods and data sources; in Section 3 we simulate the direct impact on global emissions of the geographic shift of GSCs from developed countries to China and discuss the indirect impact of that shift; in Section 4 we discuss the likely impact on GHG emissions of a GSC shift from China to its successor countries. Some policy-related implications of our findings are discussed in Section 5.

## 2. Materials and Methods

### 2.1. Global Multi-Regional Input-Output (GMRIO) Framework

We use a global multiregional input-output model (GMRIO) to trace consumption-based emissions generated in the production processes along the global supply chains (see Wiedmann (2009) for a review and Malik et al. (2016) for recent applications).[iii] In the GMRIO framework, all emissions are traced to final consumption or fixed capital formation of specific countries, which is equivalent to measuring emissions on a consumption accounting rather than production (territorial) accounting basis.

Table 1 sets out the GMRIO framework employed in this paper. The diagonal matrices of intermediate good use give the intra-country intermediate deliveries. The elements $z_{ij}^{11}$ of matrix $\mathbf{Z}$ (Jiang et al., 2015) for example, give the intermediate deliveries from industry $i$ in country 1 to industry $j$ in country 1, with $i, j = 1, \ldots, n$, where $n$ is the number of industries. The non-diagonal matrices indicate inter-country intermediate deliveries. The elements $z_{ij}^{1\mathrm{m}}$ of matrix $\mathbf{Z}^{1\mathrm{m}}$, for example, indicate deliveries of products from industry $i$ in country 1 for input use in industry $j$ in country m. The matrices of final demand have a similar structure. In contrast to the national input-output table where exports are indicated in a single column, the exports in inter-country input-output table are included in several columns of intermediate use and in final use. The exports of country 1, for example, is the sum of $\sum\limits_{\mathrm{k}=2,..\mathrm{m}} \mathrm{Z}^{1\mathrm{k}}$ and $\sum\limits_{\mathrm{k}=2,..\mathrm{m}} \mathrm{F}^{1\mathrm{k}}$.

According to Table 1, we have row equilibrium in matrix notation as:

$$\begin{bmatrix} Z^{11} & \cdots & Z^{1n} \\ \vdots & \ddots & \vdots \\ Z^{n1} & \cdots & Z^{nn} \end{bmatrix} + \begin{bmatrix} F^{11} + \cdots + F^{1n} \\ \cdots \\ F^{n1} + \cdots + F^{nn} \end{bmatrix} = \begin{bmatrix} X^1 \\ \vdots \\ X^n \end{bmatrix} \tag{1}$$

The direct input coefficients then can be obtained by normalizing the columns in the IO table. That is:

$$A^{rs} = Z^{rs}\left(\widehat{X^s}\right)^{-1} \tag{2}$$

where $r, s = 1, \ldots$, n, and $(\widehat{X^s})^{-1}$ denotes the inverse of a diagonal matrix of total outputs in country s.

Define input coefficients matrix $\mathrm{A} = \begin{bmatrix} A^{11} & \cdots & A^{1n} \\ \vdots & \ddots & \vdots \\ A^{n1} & \cdots & A^{nn} \end{bmatrix}$ where $A^{rs}$ is the input coefficient from country $r$ to country $s$. Then the Leontief inverse can be calculated as $\mathrm{B} = (\mathrm{I} - \mathrm{A})^{-1}$, that is, $\mathrm{B} = \begin{bmatrix} B^{11} & \cdots & B^{1n} \\ \vdots & \ddots & \vdots \\ B^{n1} & \cdots & B^{nn} \end{bmatrix} =$ $\begin{bmatrix} I - A^{11} & \cdots & -A^{1n} \\ \vdots & \ddots & \vdots \\ -A^{n1} & \cdots & I - A^{nn} \end{bmatrix}^{-1}$, where I is the identity matrix with diagonal elements as ones and non-diagonal elements as zeros. The Leontief inverse describes both the direct and indirect linkages across countries and sectors.

Using $E^r$ to denote GHG emission in country $r$, and $CA^r = E^r(\widehat{X^r})^{-1}$ to denote the GHG emission coefficient per unit of output in country $r$, GHG emissions generated along global supply chains (GSCs) can be

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[iii] Note in this paper we only focus on the GHG emissions generated in the productions of goods and services. The GHG emissions from land use, forest, and household activities associated with the combustion of fossil fuels (e.g. driving cars or cooking) are excluded.