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Urban economy's carbon flow through external trade: Spatial-temporal evolution for Macao

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ABSTRACT

A typical heterotrophic urban economy relies heavily on external trade, which inevitably generates carbon emissions outside its administrative boundary. Based on the most updated multi-regional input-output table, this study investigates the evolution of energy-related carbon flows embodied in Macao's external trade. The results show that both carbon inflows and outflows maintain a growing trend from 2000 to 2013 in general, accompanied with some rise and falls during this period. Total carbon imports increase from 3.67E+06 t in 2000 to 1.24E+07 t in 2013, whose main contributor changes from Sector *Textiles and Wearing Apparel* in 2000 to Sector *Electricity, Gas and Water* in 2013. Mainland China, the European Union and Japan are the main providers of carbon inflows. Dominated by gaming service exports, total carbon outflows are equal to 6.48E+06 t in 2013, which is 2.6 times that of year 2000. Macao has avoided large amounts of local carbon emissions by net carbon emission imports, indicating that the decarbonization of the urban economy achieved by transferring carbon intensive industries to other places is a bias towards sustainability. Following the results, holistic energy conservation and carbon reduction policies are proposed for Macao from both the local and global perspective.

1. Introduction

Urban economies are characterized by population and industry agglomeration (Creutzig et al., 2015). With intensive industrial and anthropogenic activities, urban economies are responsible for around 70% of global energy use and three quarters of global energy-related carbon emissions (Seto et al., 2014). The ever increasing urban population, which is projected to double by 2050 (Duren and Miller, 2012), will trigger an explosive urban expansion and infrastructure build-up, resulting in increased carbon emissions in the coming decades. Meanwhile, climate change will exert adverse impact on urban areas given that more than 80% of urban areas are located on coasts and riverbanks, making urban highly vulnerable to sea level rise, inland and coastal flooding and storm surges (IPCC, 2014; UN, 2015). Notwithstanding the challenge, urban economies are better resourced, able to operate more effectively than central government in tackling the climate change issue (Dent et al., 2015). Therefore, urban economies can make a global difference by take actions to implement carbon mitigation policies.

With globalization further intensifying the geographical fragmenting of production (Antràs and Hillberry, 2012; IDE-JETRO and WTO, 2011; Xia et al., 2017), urban economies get involved in global supply chains more deeply. On the one hand, as conventional heterotrophic systems, urban economies rely on global imports of various resources to maintain daily operation (Chen et al., 2017b; Han et al., 2015; Li et al., 2016; Meng et al., 2017). On the other hand, goods/services produced by urban economies, especially those Asian cities (Oliveira et al., 2013), may be exported to fulfill the demand of other regions worldwide. Quantities of studies have shown that considerable emissions (including many air pollutants) can be transferred through trade (Chen et al., 2017a, 2016; Davis et al., 2011; Li et al., 2017; Meng et al., 2015, 2016; Peters et al., 2011b; Zhao et al., 2015). As a result, external trade plays an increasingly important role in shaping urban economies' carbon emissions profile, making production-based or territorial based emission accounting insufficient to capture the carbon leakage (Kanemoto et al., 2012; Peters, 2008; Peters and Hertwich, 2008). There are many studies about consumption-based or carbon footprint accounting for urban economies (Feng et al., 2014; Hillman

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and Ramaswami, 2010; Lenzen and Peters, 2010; Lin et al., 2013; Ling et al., 2016; Mi et al., 2016). However, only a few studies have paid attention to combine information on global supply chains into urban carbon footprint accounting (Athanassiadis et al., 2016; Hu et al., 2016; Larsen and Hertwich, 2009; Minx et al., 2013). Even though the urban imports are directly produced by some specific economies, the emissions emitted in their upstream supply chains may be distributed all over the world. For example, an iPhone needs more than 700 suppliers of components across about 30 countries before it is finally assembled in China. If urban policies only targets on carbon emissions in the administrative boundary, the "local reduction, overall rise" phenomenon will occur. Therefore, it's necessary to track the geographical origins of these emissions along global supply chains to reveal the true emission responsibility of the urban economy. Over the past decades, urban economies have witnessed a tremendous change in economic development, population growth, trade expansion and energy demand. For example, the urbanization rate has increased from 30% in 1950 to 54% in 2014, and by 2050, 66% of the world population is projected to be urban (UN, 2014). At least 70% of global energy is consumed by urban economies (Seto et al., 2014). All these factors could impact significantly on the carbon emissions flows of urban economies. Identifying the historical temporal evolution pattern is necessary to make reliable forecasts and adjust future policies. As a result, understanding the spatial and temporal evolution of carbon flows through external trade is vital for urban economies to formulate sound reduction policies for both local and global carbon emissions.

Macao, one of the two special administrative regions, is located at the south-west corner of the Pearl River Estuary. After the handover of its sovereignty to China in 1999, Macao's per capita GDP has witnessed rapid growth with an average annual growth rate of 14.5% from 2000 to 2013. The opening of gaming right in 2002 and the abolition of Macao's garment export quotas in 2005 have resulted in the changes in industrial structure. The gaming-led tertiary industry is the pillar of Macao's economy, contributing over 80% to its GDP. The fast pace of the economic growth is inevitably supported by huge energy consumption, which has risen by almost half (Chen et al., 2017b). To optimize the energy structure and meet the ever-increasing energy demand, Macao has imported natural gas and electricity from mainland China to replace fuel and diesel used by local electricity generation. As an individual member of the World Trade Organization (WTO), Macao has closer trade relationships with many economies around the world, especially mainland China. Macao's imports and exports have maintained an average growth rate of 15.6% and 18.9%, respectively, from 2000 to 2013 (Chen et al., 2017b; Chen and Li, 2015; Li et al., 2014b). After the official ratification of Kyoto Protocol in 2008, Macao's greenhouse gas (GHG) emissions have been comprehensively investigated by many studies (Chen et al., 2017b; Li et al., 2014a, 2013; Li and Chen, 2013; To et al., 2011). However, some issues still need to be addressed. Firstly, previous studies only give a rather rough estimation by separating Macao's bilateral trade partner into mainland China and Rest of World, which cannot track the carbon emissions embodied in global supply chains. Secondly, the embodied emission intensities of a specific year are applied to evaluate the long time serial results, lowering the credibility of the results. Thirdly, where the inflow and outflow emissions originally generated remain to be explored.

Given that, this study aims to: (1) construct a long time series carbon multiplier database with country and sectoral details by applying the most updated multi-regional input-output (MRIO) database and energy-related carbon emission satellite account (unless otherwise stated, carbon emissions refer to energy-related carbon dioxide emissions in this study); (2) investigate the Macao's temporal carbon flows through external trade from 2000 to 2013 by integrating bilateral trade data with carbon multiplier database; (3) trace the geographical origins of the carbon emissions by tele-connecting Macao's imports and exports to global carbon emissions; (4) analyze the spatial and temporal evolution of carbon inflows and outflows to provide insights into the low-carbon city policies for Macao.

The rest of this study is organized as follows: methodology and data are elaborated in Section 2; Section 3 presents the results and analysis; some discussions and policy implications are carried out in Section 4; finally, conclusions are drawn in Section 5.

2. Methodology and data

2.1. Carbon multiplier database

In order to track the carbon flows in external trade, MRIO analysis is widely used to calculate the carbon multiplier with sector and country details (Lenzen et al., 2004; Minx et al., 2009; Tukker and Dietzenbacher, 2013; Wiedmann, 2009; Wiedmann et al., 2010). The global MRIO model for energy-related carbon emissions is presented in Appendix Table A4. As shown in Table A4, the global economy is modelled with an input-output monetary flow table, consisting of n economies with m sectors k kinds of final demand in each economy. z_{ij}^{sr} is the monetary value of goods or services selling from sector i in economy s to sector j in economy r, while x_i^s stands for the total output of sector i in economy s. d_i^r represents the direct energy-related carbon emissions by sector i in economy r. According to (Chen and Wu, 2017; Chen et al., 2013), the biophysical input-output balance for a sector can be calculated using the following equation:

$$d_i^s + \sum_{r=1}^{n}\sum_{j=1}^{m} \varepsilon_j^r z_{ji}^{rs} = \varepsilon_i^s x_i^s \tag{1}$$

After deduction, the general equation calculating the carbon multiplier can be expressed as:

$$E = diag(D) \times (I - A)^{-1} \tag{2}$$

where $E = [\varepsilon_{ij}^{rs}]_{mn\times mn}$ is the carbon multiplier matrix, in which ε_{ij}^{rs} indicates that embodied carbon emissions (direct and indirect) emitted by sector i in economy r induced by a unit output of sector j in economy s, with consideration of both direct carbon emissions as exogenous input from natural ecosystem and indirect carbon emissions as endogenous feedback from economic system itself; $D = [d_i^r]_{1\times mn}$ represents the carbon emission satellite matrix; $(I - A)^{-1}$ stands for the Leontief inverse matrix, in which I is the diagnosed identity matrix and $A = [z_{ij}^{sr}/x_j^r]_{mn\times mn}$ is the the direct requirement coefficient (Miller and Blair, 2009).

2.2. Carbon flows accounting

The carbon flows through external trade can be obtained by multiplying the trade data (imports and exports) and the corresponding carbon multiplier:

$$CEI^M = \sum_s \sum_j (\sum_r \sum_i \varepsilon_{ij}^{rs} \times Im_j^{sM}) \tag{3}$$

$$CEE^M = \sum_s \sum_j (\sum_r \sum_i \varepsilon_{ij}^{rM} \times Ex_j^{Ms}) \tag{4}$$

where CEI^M and CEE^M are the carbon emissions embodied in imports and exports of Macao, respectively; the superscript M stands for Macao; Im_j^{sM} represents the Macao's imports from sector j in region s; Ex_j^{Ms} is the exports of sector j in Macao to region s.

With the results of CEI^M and CEE^M, the carbon emissions embodied in trade balance CEB^M is equal to CEI^M minus CEE^M:

$$CEB^M = CEI^M - CEE^M \tag{5}$$

The external trade considered in this study includes goods and service trade, as the gaming-related service trade is the pillar of Macao's economy (Chen et al., 2017b; Chen and Li, 2015). However, unlike the goods trade, the service trade data between Macao and its trade partner is unavailable. Therefore, only the global mean carbon multiplier of