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Urban carbon flow and structure analysis in a multi-scales economy

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ABSTRACT

With the increasing threat of global climate change, carbon emissions reductions in cities have aroused the concern of the world. Carbon flow is one of the profiles that is closely connected to the urban metabolic system. Here, a global environmentally extended multi-scale input-output model was employed to accurately trace the carbon flow in a multi-scales economic system from production and consumption perspectives. Beijing was selected as the case, and the results were as follows: Beijing is typically a net importer of carbon flow (net consumer), which is consistent with Beijing's profile as a consumer metropolis. Further, all seven domestic regions in China were net producers corresponding to Beijing, supporting nearly 96.56% of the net carbon inflows driven by Beijing's final demand. Beijing mainly imports carbon flows from domestic regions and developing areas around the world, while exporting little to developed countries. Aside from the Mining (S2), Nonmetallic (S9), and Transport (S17) sectors, all other industrial sectors were net inflows of carbon for Beijing in 2010. In addition, Beijing is located at the bottom of the global production supply chain, transferring the embodied carbon flow to the origin by domestic and international imports. These results indicate that regional coordination and regional trade structure adjustment should be the main measures to tackle global climate change in the future.

1. Introduction

Currently, 54% of the world's population lives in urban areas, a proportion that is projected to increase to 66% by 2050 with the expected addition of 2.5 billion people to cities (UN, 2014). Cities around the world will face numerous problems in meeting the increasing needs of their urban populations. In fact, they already consume 67–76% of global energy (Seto et al., 2014) and produce 75% of the carbon emissions (IPCC, 2006). Cities are among the main causes of global environmental issues but could also be the place for solutions to many environmental stressors. With the increasing threat of global climate change, carbon emissions reductions in cities have aroused the concern of the world (Seneviratne et al., 2016). Urban carbon accounting induced by energy consumption has been widely conducted in recent years (Chen et al., 2017; Shao et al., 2016; Lin et al., 2013; Liu et al., 2012; Meng et al., 2017a, 2017b). Carbon flow is one of the profiles that is closely connected to the urban metabolic system (Chen and Chen, 2016; Zhang et al., 2014). It is also a valuable indicator in understanding both direct and indirect on-site and off-site greenhouse gas (GHG) emissions (Zhao et al., 2014; Lin et al., 2015; Wright et al., 2011).

Regarding CO_2 emissions at the city level, an open urban economy induces CO_2 emissions beyond its geographic boundaries via both international and domestic trade (Lin et al., 2017; Hu et al., 2016). Many studies demonstrate that a large number of virtual emission fluxes (including many air pollutants) flowing into, within, and out of the city associated with economic flows (Chen et al., 2013, 2017a; Meng et al., 2015, 2016; Shao et al., 2016; Feng et al., 2014). Considering the full impact of urban activities on global carbon emissions, accurate carbon flow analysis at the city-scale faces many challenges. Therefore, the responsibility for urban CO_2 emissions reduction should not be confined to the local government but should include collaboration among local, regional, national, and global policymakers by considering industry specializations and trade policy differences (Feng et al., 2013, 2014). The issues that need to be addressed include how to accurately trace urban carbon flows embodied in domestic and foreign trade and how to allocate responsibilities for an urban economy's carbon emissions.

Research has mainly concentrated on urban carbon flows through production-based accounting (PBA) and consumption-based accounting (CBA) approaches. Production-based or territorial-based carbon flows

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are caused by domestic production, including exports (Peters and Hertwich, 2008b). They neglect indirect carbon emissions embodied in the supply chain, resulting in carbon leakage, which undermines the effects of international climate policies (Atkinson et al., 2011; Steininger et al., 2014). Currently, the PBA approach is widely used in global climate change agreements, including the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol (Mi et al., 2016). The CBA approach allocates emissions occurring along both production and distribution to the final consumers, rather than the producers (Brizga et al., 2017). Consumption-based carbon flows include imports emissions embodied in trade, but they exclude exports. The CBA has been increasingly used in a policy context to provide an understanding of the emissions embodied in trade (Mi et al., 2016). A series of studies compare the two approaches and demonstrated the advantages of CBA (Jakob et al., 2015; Lin et al., 2015; Peters and Hertwich, 2008b). In particular, CBA opens the door to new solutions to assign carbon emissions, bringing together producers and final consumers. Moreover, it can improve both cost-effectiveness and justice, providing a more useful and straightforward evaluation of the performance of local climate actions and of the green level of upstream and downstream production technologies, resolving carbon leakage, promoting environmental comparative advantages, increasing options for CO_2 emissions mitigation, and encouraging technology diffusion (Peters and Hertwich, 2008a; Larsen and Hertwich, 2009; Chen et al., 2013; Steininger et al., 2014).

Input-Output Analysis (IOA) is the main CBA approach used to trace urban carbon flows. When city-level input-output tables are not available, life cycle analysis (LCA) is also a complementary tool for evaluating the carbon flows of an urban economy (Chen et al., 2017; Meng et al., 2017a). In previous studies, the single-regional input-output method was used to estimate urban carbon emissions embodied in imports. However, due to limited data availability, it is generally based on the homogeneity assumption that imported and domestic products from the same industries are all produced with the same technologies and that their embodied intensities are equal (Meng et al., 2017a; Mi et al., 2016). This induces inaccurate results, especially for a modern open city supported by massive domestic and foreign imports. Indeed, embodied intensities at different economy scales can vary widely due to diverse economic structures and productive technologies (Chen et al., 2013). Hasegawa et al. (2015) find that the percentage of carbon leakage to carbon emissions is more than 50% on average at the regional level, based on a multi-regional input-output (MRIO) model. Thus, it is important to differentiate the carbon flows embodied in trade and consumption at different scales.

The multi-scale input-output (MSIO) model revised from the MRIO can provide more comprehensive analysis capable of capturing the interdependencies of the global economy while preserving regional differences (Chen et al., 2011; Bachmann et al., 2014). It has been developed and often used at large scales to concentrate on contemporary issues such as greenhouse gas emissions (Wiedmann, 2009; Feng et al., 2014; Liu et al., 2016) and water footprints (Daniels et al., 2011). However, only a few studies have paid attention to urban carbon emissions accounting by extending the research scale to the global supply chains (Chen et al., 2013; Shao et al., 2017; Lin et al., 2017), mainly because city-level input-output tables are not available (Chen et al., 2017). For those existing studies, the MSIO model was used to only trace the consumption-based carbon flow and account for territorial CO_2 emissions at the point of production without consideration of where goods are used or who ultimately uses them (Atkinson et al., 2011; Steininger et al., 2014). This ignores the fact that a large amount of goods and services produced by urban economies, especially those Asian cities (Oliveira et al., 2013), may be exported to satisfy the demand of other regions worldwide; On the other hand, the MSIO model captures the relationships between the city and trading countries around the world, but it lacks domestic regional detail for China (Lin et al., 2017; Hu et al., 2016; Shao et al., 2016). Therefore, a multi-scale arithmetic for urban carbon flows is presented in this study to accurately trace the destination and source of various flows in the local, domestic regions and the worldwide economies, according to the general formulation of MRIO analysis for urban carbon emissions.

Beijing (longitude 116°25′29″ E, latitude 39°54′20″ N), the capital of the People's Republic of China, is the center of the nation's political, cultural, and education life and one of the four municipalities directly under the Central Government. It covers an area of 16,411 km^2, with a total permanent resident population of 19.60 million in 2010. During the period of 2000–2011, Beijing's economy developed rapidly, with the GDP reaching 1625.19 billion Yuan in 2011 and an average annual growth rate of 16.04% (BMBS, 2011). Especially after the Olympics Games held in Beijing in 2008, the Beijing industrial structure has been adjusted with many energy-intensive industries transferred to neighboring provinces. Beijing is in a post-industrial economy with three-quarters for the tertiary sector in 2010 compared to most other Chinese cities dominated by industrial sectors. As economies opened up after 2008, Beijing has closer relationships with many economies around the world, including mainland China regions (domestic trade) and foreign countries (international trade). This study aimed to employ an environmental-extended MSIO (EE-MSIO) modeling to accurately trace the spatial distribution of urban production-based and consumption-based carbon flow in the local, domestic, and worldwide range of the Beijing economy in 2010. The paper is organized as follows: 1) introduction to the calculating methodology and data source, 2) application of the EE-MSIO model to trace carbon flow for Beijing in 2010, and 3) drawing conclusions and policy implications based on results.

2. Methodology and data use

2.1. EE-MSIO model

The core of the EE-MSIO model, which was developed at three different scales (city, nation, and global), is a multi-regional input-output table (MRIOT) describing product exchanges within and among city-nation-globe economic systems. The objective was to merge two already existing and possibly conflicting MRIO datasets that describe different spatial scales into one multi-scale model. In particular, it links the MRIOT of Chinese provinces in 2010 with the World Input-Output Table (WIOT) in 2010, which is based on the World Input Output Database (WIOD).[1] It has the advantage that IO tables and trade flows do not need to be estimated at either scale (only trade flows linking scales) (Bachmann et al., 2015). Similar linkages have been used in previous studies (Feng et al., 2014; Mi et al., 2017; Su and Ang, 2014; Weitzel and Ma, 2014; Liu et al., 2016), and the main linking method was previously introduced in more detail by Peters et al. (2011).

In the EE-MSIO model, the world is divided into 41 nations or regions and 1435 sectors (35 sectors per nation/region) in the WIOD for each year (Dietzenbacher et al., 2013; Timmer et al., 2015). As China is one of the 41 regions in the WIOD, the Chinese IOT in the WIOD is disaggregated into 30 province-level tables, based on the IOTs within the Chinese MRIO model. This model consists of 30 provinces (including four cities), except Tibet and Taiwan. The main database of the Chinese MRIO, compiled by Liu and his colleagues (Liu et al., 2014), has been widely applied in related research (Feng et al., 2013, 2014; Liu et al., 2016). And the MRIOT of China for 2010 was the newest available data currently. The WIOD's international import and export matrices for China were also disaggregated and allocated to the 30 provinces, based on provincial exports and imports in the Chinese MRIOT. International exports for each sector in each province were distributed among importing sectors in foreign countries at the same ratio as China's total exports. The detailed equation follows:

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[1] http://www.wiod.org.