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Ecological network analysis for urban metabolism and carbon emissions based on input-output tables: A case study of Guangdong province

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ABSTRACT

Global warming has received more and more attention in recent years for its inevitable influence on population, species, soil, ocean, water and so on. It is essential to investigate the urban metabolism of carbon emissions which is a main cause of global warming and most of it occurs in the process of production and living in urban areas. In this paper, a carbon emission metabolic network is established to explore the emission reduction strategies by modeling carbon dioxide flows and identifying the mutual relationships based on the input-output analysis. Specifically, Eff-Lorenz curve derived from the painting of Lorenz curve is developed to compare the efficiency of carbon emissions from different sectors. The newly developed method has been applied to Guangdong province to demonstrate its availability and benefit. It is revealed that carbon emissions mainly concentrated in the secondary and tertiary industries with electric power generation, manufacturing industry, domestic consumption and transportation ranking at the top. The competition relationship reveals good interactions in terms of emission reduction while a mutualism relationship provides effective pathways to mitigate carbon emissions between pairwise sectors simultaneously. In Guangdong province, upgrading the clean combustion technology in electric power generation and energy extraction sectors would drive other sectors to cut emissions and adjusting the production structure of the construction sector also contribute to achieve this goal. The results are expected to provide corresponding and holistic reference for decision makers to develop the mitigation policies.

1. Introduction

As a part of atmosphere, carbon dioxide is mainly produced by the burning of carbonaceous material, animal metabolism, land cover and anthropogenic activities. Although carbon dioxide is essential in the process of urban metabolism and economic activities, excessive existence of it, as the main component of greenhouse gases, is responsible for global climate change and anomalies (Karl and Trenberth, 2003; Ofipcc, 2013). Carbon dioxide has an excellent thermal insulation effect which can coat the earth with a thick “down jacket” (Coles, 2003; Kosugi, 2009). In the last century, the global temperature was increased by 0.6 °C (Cox et al., 2000), accompanied with the rise of sea level (Frölicher and Joos, 2010; 2009), the shifts of species (Davis et al., 1998), the widespread of epidemic disease (Pounds et al., 2006), the decline of rice yields (Peng et al., 2004; Swain, 2010) and so on. The global warming seriously affected the economy development and caused great threat on the security of socio-economic system (Root et al., 2003; Logan et al., 2003). Therefore, it is important to connect the “invisible hands” into “visible data” and investigate the mechanism of the urban metabolism system, which will further help to alleviate the pressure of carbon emissions (Wolman, 1965).

In the early days, due to the limitations of statistical methods and technologies, carbon emission data were difficult to be obtained. Carbon cycle attracted scholars' attention and a vast of case studies have been conducted, including the middle latitudes in the northern hemisphere (Levin and Kromer, 2004), North America (Pataki et al., 2006), Toronto (Sahely et al., 2003), Beijing (Feng et al., 2013), Guangyuan (Hao, 2017) and so on. Bolin (1970) studied the carbon dioxide in the atmosphere and referred to the global carbon cycle. Larsen and Hertwich (2009) tracked the impact of carbon footprints on climate changes based on consumption. A full carbon cycle analysis developed by West and Marland (2002) has been completed for agricultural inputs, resulting in estimates of net carbon flux for three crop types across three tillage intensities.

With the development of statistical technology and the intensification of global warming, the research on carbon emission is increasing.

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Carbon emission has become a hot issue in the field of resource and environment. Many scholars have studied the strategies in emission reduction and the influencing factors from different perspectives. Dietz et al. (2009) proposed that the potential of household action deserves increased policy attention and domestic consumption has a strong bear on carbon emissions. Ali and Abbas (2013) found that use of multiple tools and techniques deliver better results in carbon emission mitigation tracer research. The expert system was developed by Zhou (2015) to enhance performance and efficiency of the CO_2 capture process. Through comparing the changes in urban energy uses and CO_2 emissions in China, it was shown that the 35 largest cities in China, which contain 18% of the population, contribute 40% of China's energy utilization and CO_2 emissions (Dhakal, 2009). Although the research object is different, the similarity of these literatures mentioned above is related to the research of carbon element. Most of the researches only analyze the impact of one sector (such as domestic consumption and energy utilization) on carbon emissions rather than the overall analysis of different industrial sectors. Specifically, these researches didn't involve the carbon emissions generated by intersectoral interactions.

Later, in order to study the flows among various sectors in the system and realize the mutual transformation of economic data and ecological elements, the methodologies proposed by Leontief (1974; 1952) were widely applied to analyze specific cases (Leontief, 1936). After that, scholars introduced the specific calculation methods and formulas using monetary input-output tables to compile the corresponding physical input-output tables (Duchin, 2004; Zhang et al., 2014a,b). Many ecological elements have been analyzed through this method, such as virtual water, energy, carbon and so on. For instance, Fang et al. chose ecological network analysis based on input-output tables as a useful tool to examine the structure and function of virtual water network and the interactions among sectors (Fang and Chen, 2015). Dai et al. (2014) developed an extended exergy-based sustainability indices system which had been established to provide an epitomized exploration for evaluating the performance of flows and storages with the system from a sustainability perspective. Yang et al. (2012) addressed the issues of the indirect effects of virtual water trade through the global economic circulation and used ecological network analysis (ENA) to shed insight into the complicated system interactions. As one of the key elements in the urban metabolism system, carbon has been investigated based on ENA. Chen and Chen (2012) developed a carbon flux model based on network environ analysis within the urban ecosystem of Vienna. A carbon metabolic network has been constructed by modeling the carbon flows between economic sectors and environment by Chen et al. (2015a, b). A model that integrated the carbon cycle with economic activities in the 2002 U.S. economy was developed by Singh and Bakshi (2015). Economic activities can be captured through the economic input-output model. They studied carbon rather than carbon dioxide. From the perspective of the application of I–O table, there are many research on carbon or other elements but few analyses about carbon emission. Therefore, the study of carbon emission metabolism based on input-output tables is rare and necessary.

In recent years, the population of Guangdong province has maintained a sustained growth trend. In 2012, with GDP ranking first in China, Guangdong province has the largest population as well, accounting for 7.3% of the total population. At the same time, the rapid development of economy brought up a large amount of carbon emissions. In terms of the metabolism of carbon emissions, Guangdong's per capita carbon emission is much higher than some cities of developed countries, such as the United States, Japan and so on. Moreover, from 2000 to 2012, the total carbon emissions of Guangdong province increased year by year, which needs extensive attention. Carbon dioxide generated indirectly by the various industrial sectors is an important study content comparing with direct emissions. Metabolism hidden between sectors which appear to be no carbon emission flows is the focus of research. In addition, carbon emission metabolism of various sectors varies significantly due to the compound complexity and diversity in the system. The specific studies on each sector's emission performance are of great significance for generating effective emission reduction measures and overall development planning (Wilbanks and Kates, 1999).

However, at present, there are limited researches on carbon emissions in Guangdong province, with most of them are focused on the direct emissions. The previous input-output analysis for other regions can only reflect the local situation around the administrative boundaries (Chen et al., 2010, 2015a,b). The results of a certain area couldn't be extended to Guangdong province, since the difference of economic development degree and population level. What's more, most previous studies focused on the impacts of a single sector on carbon emissions, while the systemic impacts of other sectors were ignored.

Therefore, the objective of this study is to get a holistic assessment of the carbon dioxide flows among sectors of Guangdong province in 2012 and give a comparison of the efficiency of carbon emissions between Guangdong and the whole nation. In detail, a carbon emission metabolic network encompassing the urban economy and environment will be proposed. The direct and indirect flows among sectors and four types of ecological relationships will be compiled with methodology derived from input-output analysis. The dependences of one sector on other sectors will be presented to illustrate the sector's control and dependence over the system. What's more, an Eff-Lorenz curve will be developed for the thirteen sectors in Guangdong province to further compare the efficiency of different sectors in the system. The results of this study are expected to find the sectors conductive to reducing the carbon emissions and provide assistant in policy formulation.

2. Materials and methods

2.1. Structure of network model

Carbon emission network (CEN) model is developed to illustrate the interactions and flows among different sectors. Here, carbon emissions refer to the carbon dioxide emitted to the environment. The CEN model is established based on the economic input-output model framework via incorporating with statistic data about carbon emissions of each sectors. CEN consists of thirteen distinctive sectors: agriculture sector (Agr), energy production sector (CPG), mining sector (Min), manufacturing sector (Man), Electric Power, Steam and Hot Water (ESW), gas (Gas), tap water (TW), construction sector(Con), transportation sector (Tra), wholesale, retail trade and catering(WRC), service sector (Ser) and domestic consumption (Dom).

For the monetary input output tables, the rows of such a table describe the distribution of a producer's output throughout the economy and the columns describe the composition of inputs required by a particular industry to produce its output (Simpson and Tsukui, 1965). We defined that the direction in f_{ji} is from sector i to sector j. Embodied ecological element intensity enabled the conversion of the monetary input and output value flows to carbon dioxide flows among sectors, which could be calculated by Eqs. (1) and (2) (Zhang et al., 2014a,b).

$$\mathrm{P} + \varepsilon \mathbf{H} = \varepsilon \mathbf{U} \tag{1}$$

where $\boldsymbol{H}$ represents the value flow among sectors, $\boldsymbol{U}$ is a diagonal matrix composed of the total output of each sector, $\boldsymbol{P}$ is the initial resource or waste that flow into or out of the sector. Here, carbon emission is the negative ecological element we are going to discuss as the initial input. Then:

$$\varepsilon = \mathbf{P}(\mathbf{U}\text{-}\mathbf{H})^{-1} \tag{2}$$

where ε_i represents the embodied intensity of sector i. Let the embodied intensity matrix multiply the corresponding flows in the value matrix $\boldsymbol{H}$. Then the final physical input-output tables is established, which can be referred in Table S6.

In the CEN model, f_{ji} contains carbon dioxide flows among sectors with the direction from the production side to others on the