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Flow analysis of the carbon metabolic processes in Beijing using carbon imbalance and external dependence indices

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ABSTRACT

Maintaining urban systems consumes a large amount and variety of materials and leads to waste flows. Carbon is a basic element that intuitively characterizes the metabolic characteristics of urban resource consumption and pollution emission. In this study, we integrated the carbon metabolic flows among 18 metabolic actors and between these actors and the atmosphere, and calculated flows of material in many categories using empirically derived coefficients to estimate the associated carbon flows (emission and absorption). Taking Beijing as an example, we analyzed the dynamic changes in the carbon metabolism and the structural characteristics of material utilization. We defined two indices to characterize the metabolism (the carbon imbalance and external dependence indices), and identified key actors responsible for changes in the indices. The total carbon metabolism (inputs and outputs) increased by 64% and 200%, respectively, from 1995 to 2015, mainly driven by energy consumption, which accounted for more than 78% of the total. In addition, input growth was driven by food, accounting for up to 6% of the total. The carbon imbalance and external dependence indices increased to nearly two and four times their 1995 values, respectively, mainly due to the Manufacturing, Electricity and Heat Production, and Energy Conversion actors' demand for food or energy during the early part of the study period, and by the rapid growth of food or energy required by the Urban Life and Transportation actors. Identifying and comparing the key metabolic actors provided a novel way to analyze data to determine targets for carbon regulation and emission reduction measures for Beijing.

1. Introduction

A report released by the C40 Urban Climate Leadership alliance and the Carbon Disclosure Project Organization stated that cities accounted for 70% of global carbon emissions (KPMG, 2011). This results from high consumption of energy, food, and minerals by cities (Musango et al., 2017), where the vegetation can only offset 8% of the emission that results from this consumption (Escobedo et al., 2010). This imbalance produces serious resource and environmental problems. Beijing, one of the largest of the C40 cities, has shown a 53% increase in the consumption of fossil fuels, biomass, and minerals since 1992 (Dai et al., 2017). The materials provided by Beijing's external environment increased from 30% of total consumption in 1992 to 60% in 2014, thereby exacerbating the dependence of production and life on external resources. These consumption problems have many causes, including low utilization ratios (Beijing's resource utilization efficiency in 2010 was only 1/8th of the highest level in the world) and high emission of pollutants. The surge of CO_2 emission (which increased to 2.5 times its 1995 level by 2015) attracted widespread attention (Zhang et al., 2015). At the same time, carbon absorption by vegetation was less than 10% of the emission, increasing the problems faced by Beijing's environment. These problems result from a disorder of urban carbon flows, including carbon transfers among the production and living sectors and carbon emission and absorption between sectors and the atmosphere. To support efforts to mitigate carbon emissions, it is necessary to consider these carbon flows from a metabolic perspective and analyze the degree of disorder in the carbon metabolism caused by each sector and its interactions

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with other sectors. The present study describes a new way to approach such studies by quantifying these imbalances.

Wolman (1965) first proposed the urban metabolism framework for studying shortages of water and the water and air pollution caused by urbanization. His framework provides a clear way to understand the material flows entering a city, and how human activities produce a series of wastes through consumption of these materials. Because the carbon in greenhouse gases is an important waste created by urban processes, it must also be accounted for. To find ways to cope with the global climate change created by this waste, researchers have increasingly focused on the theoretical perspective of urban carbon metabolism, which took urban metabolism as the theoretical framework and data base (Blečić et al., 2014; Kennedy et al., 2011; Pataki et al., 2006). Baccini (1996) was the first urban metabolism researcher to mention “carbon metabolism”. He divided the Swiss Lowland region into three metabolic actors: residential areas, farmland, and forest. He studied carbon fluxes among these actors and between them and the atmosphere, as well as the resulting changes in their carbon stocks. These fluxes included inputs of food and fuels, outputs of wastes, carbon transfers among the actors, and CO_2 emission and absorption between sectors and the atmosphere. Subsequently, carbon metabolism appeared in a report on the urban metabolism of Vienna, Austria (Obernosterer et al., 1998). Researchers divided the city into four metabolic actors: the atmosphere, humans, soils, and water. However, the carbon metabolic processes were similar to those of Baccini.

These early studies considered the socioeconomic actor as a “black box”, and did not analyze the carbon flows among the actors inside the box. More recent studies of urban carbon metabolism have focused on refinement of the metabolic actors. For example, researchers have defined metabolic sectors based on input–output tables and studied the embodied carbon transfers among a city's production and living sectors (Zhang et al., 2014b; Zheng et al., 2016). Others have studied carbon from the perspective of production and consumption (Yang et al., 2015). Because these studies did not consider natural actors (e.g., vegetation growing inside a city), researchers added the natural actors by accounting for a city's diverse land use types. Carbon metabolic actors have been divided into groups based on different land use types to allow analyses of the impact of land use planning on carbon emission (Blečić et al., 2014), and the spatial patterns of urban carbon emission and absorption have also been studied (Xia et al., 2016, 2017; Zhang et al., 2014a, 2016b). In addition, researchers have divided the actors among industrial sectors and land use types to study the sectoral distribution of urban carbon emission (Zhang et al., 2015). The most distinctive characteristics of this research are that it has examined multiple sectors and multiple materials, thereby providing increasingly deep insights into the urban metabolism. In particular, these studies have begun to reveal details of what happens inside the black box.

In summary, early studies of urban carbon metabolism covered the most important processes, including carbon transfers among actors, as well as carbon emission and sequestration. Nonetheless, the division of actors remained simplistic. Later research continued to refine the socio-economic actors, but did not always analyze carbon flows among the actors. As these flows within the black box are clearly important, researchers began looking for ways to analyze them.

To provide more precise insights, researchers have focused on smaller scale in urban range, or one metabolic actor of cities, or a kind of substance that contains carbon. To focus on smaller scale in urban range, Kellett et al. (2013) narrowed the range of their research to the community of south-central Vancouver, Canada, and refined the carbon metabolic actors into the buildings and the transportation, human, vegetation, and soil components. Lu et al. (2015) selected an ecological industrial park in Beijing, and divided it into six actors: energy supply, infrastructure, household, industrial and commercial, waste disposal, and artificial landscape. They analyzed the carbon transfers among these sectors and between the sectors and Beijing's external environment. To focus on one metabolic actor of cities, Ye et al. (2011) studied the relationships between the characteristics of household buildings and carbon emissions in Xiamen, China. Lee et al. (2016) studied energy consumption and carbon emission by different types of transportation in the city of Birmingham, U.K. To focus on a kind of substance that contains carbon, Lin et al. (2016) chose food, and studied the related carbon metabolic processes for Xiamen, China, including food consumption, human digestion and absorption, excretion, and waste disposal. Kennedy et al. (2010) divided the urban metabolic actors according to the end uses of different kinds of energy, and established a method for obtaining a greenhouse gas inventory. Their analyses of system components such as transportation and buildings, and the flow directions of food and energy, enriched our knowledge of urban carbon metabolism by identifying metabolic actors and the paths between them.

Research on carbon metabolic processes relies heavily on accurate carbon accounting. At present, the accounting system for carbon emission and absorption is relatively mature (Carney et al., 2009; IPCC, 2006; Zhang et al., 2015). As a result, researchers have quantified carbon flows among components of the urban system, including families, farmland, livestock breeding, and waste disposal. For instance, Rimhanen and Kahiluoto (2014) studied crops using empirically derived coefficients for carbon contents, field samples, and mass-balance equations, and analyzed the carbon distribution in flows related to crops, including the flows of food to humans, of carbon released into the atmosphere through fuel combustion, of feed to livestock, of straw into the soil, and of waste into the composting system. They also accounted for losses in the allocation process. On this basis, Zhang et al. (2016a) focused on livestock feed and used material-flow analysis to calculate the feed inputs, as well as the digestion, storage, and excretion of carbon by livestock in the animal husbandry system. Luo et al. (2008) studied the carbon flows related to food consumption by 1000 Beijing households using a survey and empirically derived coefficients. Baker et al. (2007) expanded the list of carbon-containing substances from food to include energy, paper, plastics, fertilizer, and the wastes generated from their consumption. They then used material-flow analysis and empirically derived coefficients to calculate the carbon flows of 35 suburban families. Based on Baker et al.'s method, Fissore et al. (2012) further expanded the number and scope of the investigated families, including 360 families from both rural and urban areas, and they accounted for the input and output carbon flows of “courtyards”, including the inputs of dog droppings and the outputs of leaves and grass from lawn mowing.

These studies related to resource consumption, conversion processes, and subsequent waste production. Some researchers also focused on the subsequent waste disposal. Tonini et al. (2014) analyzed the carbon flow processes involved in refining and processing wastes, including waste inputs, pretreatment, screening, post-processing, recycling, and final disposal, and used elemental analysis (i.e., tracking the flows of an individual element) to quantify the carbon flows. Similarly, Zhou et al. (2015) studied the garbage disposal system using empirically derived coefficients to quantify the waste carbon stock and carbon inputs of the system. These studies provided methods and data for analyzing and quantifying the flows of carbon among the actors in an urban carbon metabolic system.

Early studies based on the urban metabolism theoretical