Ecological Modelling 316 (2015) 144–154

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Analysis of urban carbon metabolic processes and a description of sectoral characteristics: A case study of Beijing

Yan Zhang[a,*], Juan Li[a], Brian D. Fath[b,c], Hongmei Zheng[a], Linlin Xia[a]

[a] *State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Beijing Normal University, Xinjiekouwai Street No. 19, Beijing 100875, China*
[b] *Biology Department, Towson University, Towson, MD 21252, USA*
[c] *Advanced Systems Analysis Program, International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria*

ARTICLE INFO

Article history:
Received 15 May 2015
Received in revised form 11 August 2015
Accepted 12 August 2015

Keywords:
Urban metabolism
Catabolism
Anabolism
Technological metabolism
Carbon accounting
Carbon imbalance

ABSTRACT

Global climate change has aroused widespread interest in reducing carbon emissions and increasing carbon sequestration. Thus, an urban carbon inventory must consider both emissions and sequestration. In this context, we analyzed the main contributors to the flows that comprise a city's carbon metabolic processes employing methods and concepts from ecological science. The carbon emissions and sequestration by urban carbon metabolic processes can be compared to ecological catabolism and anabolism, respectively. We used empirical coefficients to estimate the rates of carbon catabolism and anabolism and calculate the resulting carbon imbalance index. Our analysis reveals the contributions of individual metabolic actors and the distribution of the metabolic flows among them. Taking Beijing as a case study, we found that the catabolic rate of the metabolic actors was more than five times the anabolic rate from 1995 to 2010, leading to a carbon imbalance index that was twice the average Chinese level. The major catabolic actors were the other services and domestic sectors. These catabolic rates were primarily influenced by the flows of electricity, heating energy consumption, and mobile energy consumption. The overall carbon imbalance resulted from greatly reduced metabolic flows in farmland anabolism due to conversion of farmland into urban land. Identifying the metabolic actors and flows in this manner will inform government mitigation efforts by identifying where reduction is required and guiding planning of appropriate mitigation actions. Our study also provides directions for conservation of the urban ecological environment.

1. Introduction

The surge of urban carbon emissions and the decline of carbon sequestration since the start of the Industrial Revolution have severely disturbed global carbon cycles, with potentially severe consequences for ecosystems and subsequently for socioeconomic systems; this has led to considerable research into carbon cycle dynamics (Grimm et al., 2008; IPCC, 2007; Yong, 2011). Therefore, the C40 Cities Climate Leadership Group (www.c40.org), the Local Governments for Sustainability (ICLEI; www.iclei.org), and the World Resources Institute (www.wri.org) released the Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (www.ghgprotocol.org/city-accounting). Their goals were to reduce urban carbon emission and track the effectiveness of local policies designed to reduce emission (Wade, 2014). The data suggest that urban carbon emission account for 67% to 80% of the global total (Satterthwaite, 2008). Simultaneously, urban development has greatly reduced the green areas that can absorb CO_2 (Nowak, 2000). The net result is increased CO_2 emission and decreased CO_2 sequestration. The problem of carbon emission in Chinese cities is particularly prominent given the immense scale of many of these cities and a strong trend toward increasing urbanization. Beijing currently has more than 20 million people and is one of the C40 cities. From 1995 to 2010, Beijing's energy consumption almost doubled (NBS DES, 2011). In addition, the growth of non-energy activity was also significant. For instance, the amount of waste disposal increased by a factor of more than six during this period (BMBS and NBS, 2011). These activities caused carbon emission to increase sharply. The problem has been exacerbated by the shrinking area of forest resources due to urbanization. As well, the quality of the remaining forest is not high, as the average carbon storage per unit area is only 40.1% of the mean national level, and only

---

* Corresponding author. Tel.: +86 10 5880 7280.
E-mail addresses: zhangyanyxy@126.com (Y. Zhang), lijuan4021@126.com (J. Li), bfath@towson.edu (B.D. Fath), zhenghongmei82@163.com (H. Zheng), linlinxia@mail.bnu.edu.cn (L. Xia).

http://dx.doi.org/10.1016/j.ecolmodel.2015.08.008
0304-3800/

28.6% of the global average level (BMCDR, 2010). These factors have created a gradually intensifying carbon imbalance, with a corresponding increase in the disorder of the country's carbon metabolic processes. In this context, it is urgent to answer the following questions: How can we describe the urban carbon metabolism? What are the contributions of the actors involved in carbon emission and absorption to urban carbon metabolic processes? How can we evaluate the degree of disorder in these processes? What activities are primarily responsible for this disorder? Answering these questions will provide a scientific basis for the formulation of policy and the implementation of measures to reduce carbon emission and enhance carbon sinks.

Wolman (1965) proposed the use of input–output analysis to study urban metabolism. This analysis provides a good framework for research on carbon metabolic processes (Pataki et al., 2006). However, although such analyses provide a good overview of a system, they represent a "black box" approach that ignores the details of the flows within a system, and therefore provide no support for efforts to correct imbalances in an urban metabolism. Baccini (1996) was one of the first researchers who attempted to solve the problem by focusing on the urban "carbon metabolism", which provides stronger insights into the inner workings of a city. Subsequent researchers have examined the carbon metabolic process at a range of scales, such as a comparative analysis of 10 cities (Kennedy et al., 2010), analysis at a family scale in Xiamen (Ye et al., 2011), analysis of a community in South Central Vancouver (Kellett et al., 2013), and analysis of the city of Florence (Blečić et al., 2014). Ye et al. (2011) described the effects of different architectural features on energy utilization and carbon emission. Blečić et al. (2014) presented an analytical framework to simulate the effect of different land-use planning scenarios on carbon emissions. In addition to the socioeconomic aspects of carbon metabolism, some scholars also focused on the biological metabolism. For example, in the case of Hong Kong, Newcombe et al. (1978) analyzed the metabolic processes of the human population. Kennedy (2012) accounted for canopy carbon fixation by trees in Toronto. Kellett et al. (2013) simulated the processes of carbon uptake and storage by vegetation, and carbon emission from fossil fuel combustion, in an urban community. In summary, the urban metabolism perspective lets researchers integrate the natural and artificial processes that together form an urban carbon metabolism and provides a strong accounting basis for studies of carbon emission and absorption.

In 1991, the International Council for Local Environmental Initiatives (ICLEI) started an initiative to account for urban carbon emissions, and they implemented plans for reducing urban CO_2 emissions (ICLEI, 1993). Taking advantage of their accounting system, Harvey (1993) accounted for carbon emissions from energy consumption and waste disposal in Toronto and found that combustion of fossil fuels to produce energy was the main contributor to the city's carbon emissions. Subsequent researchers took advantage of this insight and focused on carbon emissions from energy consumption, including studies of the transportation and construction sectors of 100 American cities (Brown et al., 2009), Pittsburgh (Hoesly et al., 2012), three industrial sectors in Shanghai (Li et al., 2012), and 28 sectors in four Chinese municipalities and Macao (Li and Chen, 2013; Liu et al., 2012). Brown et al. and Li et al. considered only direct carbon emissions, but the other researchers also considered indirect carbon emissions caused by inputs of electricity from outside the urban system. In addition to the carbon emission produced to generate energy, waste disposal produced a large amount of CH_4 emissions due to excessive concentration of the urban population and inefficient treatment of its organic wastes (Baldasano et al., 1999; Dubeux and La Rovere, 2007). The non-energy carbon emissions from industrial processes (such as mining, smelting, and the chemical industry) and agricultural activities have also received considerable attention. Gurjar et al. (2004) considered carbon emissions from Delhi in recent decades, and found that a significant increase in industrial growth and agricultural activity was one of the primary reasons for an increase in the city's carbon emission. Chinese research in the cities of Shenyang and Xiamen confirmed this finding (Lin et al., 2013; Xi et al., 2011).

As such studies expanded the scope of the accounting, some organizations have established carbon accounting systems and trading frameworks. At present, the research related to these systems generally uses empirical coefficients provided by IPCC (2006). Other organizations have constructed accounting systems to deal with different scales, including the GRIP system for the European Metropolis (Carney et al., 2009), the ICLEI system (mentioned above) for cities, and the World Resources Institute/World Business Council on Sustainable Development system for enterprises (WRI/WBCSD, 2009). Based on the research that led to these systems, Ramaswami et al. (2008) accounted for the carbon emission of Denver at three scales, and distinguished between carbon emission inside and outside of the city's boundary. Although the focus and objectives differed among these organizations, they all provided empirical coefficients that can be used in carbon accounting and that have greatly reduced the difficulty of such accounting.

On an urban scale, some scholars have studied the effects of woodlands, grasslands, and farmland. Forests are often the main carbon sink in a city because of their large and perennial biomass (Escobedo et al., 2010). Many studies have therefore represented forest carbon sequestration using tree volume (Nowak et al., 2013; Rowntree and Nowak, 1991). However, an approach based on tree volume fails to account for litter, dead wood, and organic matter supplied to the soil by trees. Thus, the volume-based sequestration values underestimate the actual carbon sequestration by an ecosystem. Several calculation methods have been developed to account for this problem, including an empirical coefficient method (Rowntree and Nowak, 1991), field sampling (Nowak and Crane, 2002), and field sampling combined with analysis of remote-sensing images (Nowak et al., 2013; Yang et al., 2005). A few studies have represented carbon sequestration by trees using NPP. These researchers selected field sampling (Zhao et al., 2010), or field sampling combined with analysis of remote sensing images (Wu and Bauer, 2012). Grasslands have also received some attention, as they are an important component of some urban landscapes. Researchers have generally used field sampling combined with remote sensing to measure grassland NPP (Wu and Bauer, 2012). Similarly, farmland represents an important carbon sink and an equally important carbon source that cannot be ignored (Prince et al., 2001) because the carbon absorbed by crops in one region may be released in another region when the crops are consumed (West et al., 2011), and as a result, carbon uptake may not equal carbon release for a given study area. These studies have provided experimental parameters and empirical coefficients that have improved estimates and modeling of carbon cycles.

Land use and cover types also strongly affect the magnitude of carbon sinks and sources in a terrestrial ecosystem. Thus, scholars have focused on calculating the carbon absorption capacity of different types of vegetation. Studies have focused on absorption at regional, national, and global scales to estimate the carbon absorption ability of ecosystems such as forest (Mohren et al., 2012) and grassland (Acharya et al., 2012). Some scholars adopted the method of measuring sample biomass to calculate net primary productivity (NPP; e.g., Talhelm et al., 2014). However, NPP does not account for CO_2 emission from soil respiration. The value of NPP is therefore greater than the actual carbon sequestration by natural ecosystems. Moreover, there are onerous labor and time requirements in this approach that make it difficult to adopt this method for large areas. One solution is to use net ecosystem production (NEP) to simulate the net carbon absorption capacity of an ecosystem, as has been done on a large scale for global forests and