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ECOMOD-7400; No. of Pages 7
ARTICLE IN PRESS
Ecological Modelling xxx (2014) xxx–xxx
Contents lists available at ScienceDirect
Ecological Modelling
journal homepage: www.elsevier.com/locate/ecolmodel

# Modeling the carbon cycle of the municipal solid waste management system for urban metabolism

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ARTICLE INFO

*Article history:*
Available online xxx

*Keywords:*
Carbon cycle
Carbon stock
Model
Urban metabolism
Municipal solid waste

ABSTRACT

Municipal solid waste management is one of the key subsystems of urban metabolism, which significantly impacts urban carbon cycles. A conceptual model for analyzing the carbon cycle of the municipal solid waste management system was established based on the theory of urban metabolism with regard to urban carbon cycling. The model includes horizontal fluxes, vertical fluxes and carbon stocks of the waste managing processes such as waste collection, transportation, treatment and disposal. The current carbon cycling of the municipal solid waste management system and two other scenarios were analyzed using a Jingmen City case study. The results indicate that the input horizontal flux in municipal solid waste between 1989 and 2004 was 293.47 Gg. Among all of the considered scenarios, the landfill formed the largest carbon stocks; incineration showed the largest vertical fluxes of carbon dioxide, and source separation and integrated technologies decreased carbon emissions by adding new carbon sources to the urban system. Improving municipal solid waste management using techniques, such as waste minimization, source separation, recycling, technical innovations of incineration, compost and digestion of organic waste, landfill mining, etc., could impact the urban carbon cycle by reducing carbon emissions.



## 1. Introduction

The concept of urban metabolism was put forward by Wolman (1965), and Kennedy further defined urban metabolism as the summation of social economic and technological processes that result in urban development, energy production and waste emission (Kennedy et al., 2007). Urban systems play an important role in the global carbon cycle, and the carbon dioxide emissions of urban systems are typically approximately 80% of the total carbon dioxide emission (Svirejeva-Hopkins and Schellnhuber, 2006, 2008). In an urban system, carbon is input in terms of food, fossil fuel, goods, etc., and it is processed and transformed within human society; a portion of the carbon is then stocked in the urban system, while the other part is output as solid waste, wastewater and waste gases (Lebel, 2005; Chen et al., 2011a,b; Chen and Chen, 2012; Li et al., 2013). The municipal solid waste management (MSWM) system is not only a subsystem of the urban system (including production, consumption, logistics and recovery), but also a self-organized social–economic–natural complex ecosystem that has environmental impacts on rivers, lakes, underground water, soil, air, plants and the landscape (Zhou et al., 2011).

The MSWM system is one of the major sources of carbon emissions in an urban system. Almost all of the municipal solid waste management processes produce carbon emissions in the form of carbon dioxide and methane, including processes of collection, transportation, compost, digestion, incineration and landfill. Solid waste was listed as an independent chapter in the *Guidelines for National Greenhouse Gas Inventories* by the Intergovernmental Panel on Climate Change (IPCC, 2007). Between 1990 and 2005, the global methane emissions from the solid waste in landfills were estimated to have increased by approximately 12%, from 706 to 792 $MtCO_2e$, ranking fifth among all non-$CO_2$ emission sources (USEPA, 2012). The municipal solid waste treatment projects aimed at reducing carbon emissions were active in the global carbon exchange

*Abbreviations:* MSW, municipal solid waste; MSWM, municipal solid waste management; GHGs, greenhouse gases; LFGs, landfill gases; LF, scenario 1/landfill; INC, scenario 2/incineration; SIT, scenario 3/source separation and integrated technologies; IPCC, Intergovernmental Panel on Climate Change; CDM, clean development mechanism.

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http://dx.doi.org/10.1016/j.ecolmodel.2014.11.027

market under the framework of the clean development mechanism (CDM).

More and more attention has been directed toward the carbon cycling of MSWM, and some progresses have been made in this field in the recent years. The generation and immigration of landfill gases (LFGs) and the controlling methods were first studied (Chai et al., 2010), and then carbon emissions were widely considered with respect to source separation, waste collection routine, treatment technologies (e.g., landfill, incineration, compost, anaerobic digestion of organic fraction of MSW, etc.) and decision-making tools (Calabrņ, 2009; Bastin and Longden, 2009; Mühle et al., 2010; Fdez-Güelfo et al., 2012). The municipal solid waste (MSW) greenhouse gas (GHG) emissions and carbon footprint were chosen as important indicators for evaluating the efficiency of the MSWM system in previous studies (Khoo et al., 2010; Couth and Trois, 2010). Multiple methods, such as the life cycle analysis (LCA), the GHG inventories of the IPCC and the first-order decomposition model (FOD) have been applied for carbon emission analysis, using the data from statistics, laboratory testing and field studies (Kumar et al., 2004).

Many studies have recognized the importance of the modeling of the MSWM system, for example, Beigle et al. (2008) analyzed the models of municipal solid waste generation, and Kollikkathara et al. (2010) and Gunalay et al. (2012) analyzed the economic and policy making models of municipal solid waste management, and Pires et al. (2011) summarized multiple systems analysis models and tools that were used in the waste management practice in European countries. But in the view of urban metabolism and urban carbon cycle, systemic models for analyzing the carbon cycling of the whole MSWM system (including the carbon fluxes, flows, stocks and their relationship, etc.) were rarely discussed in previous reports. In this research, we try to establish a systemic and conceptual model based on the theory of urban metabolism and the urban carbon cycle. And then we model the carbon fluxes and carbon stocks of the MSWM system in the studied case, Jingmen City in central China, using integrated methods of simulation, lab analysis and field studies. This work may be helpful for assessing, planning, optimizing and making policies for better municipal solid waste management systems.

## 2. Materials and methods

### 2.1. Conceptual carbon cycle model of the MSWM system

Galina (2008) described the spatial structure of the urban system as consisting of the urban sprawl and the urban footprint. The carbon cycle in the urban system includes carbon fluxes (vertical fluxes and horizontal fluxes) and carbon stocks (pools). The vertical fluxes are the carbon that migrated and released to the atmosphere, hydrosphere and lithosphere, while the horizontal fluxes are the carbon that exchanged from the urban sprawl areas and urban footprint areas (crops, forests, wastes). Based on the conceptual model of the urban carbon cycle, a carbon cycle model of the MSWM system was established (see Fig. 1).

#### 2.1.1. Horizontal fluxes

The horizontal fluxes consist of the carbon exchanges between the urban system and the municipal solid waste management system, including the following elements: (i) direct horizontal fluxes, consisting of transportation of the municipal solid waste generated from the urban inhabitants to the MSWM system, transportation of the compost produced from organic waste to urban green land, and transportation of the regenerated materials (paper, plastic, rubber, concrete, etc.); and (ii) indirect horizontal fluxes, consisting of the fossil fuel consumed for collecting, transporting, treating and disposing of the MSW.

#### 2.1.2. Vertical fluxes

The vertical fluxes include the carbon exchanges between the MSWM system and the atmosphere, hydrosphere and lithosphere: (i) direct vertical fluxes, covering methane and carbon dioxide emissions through the anaerobic digestion and aerobic biodegradation, the carbon dioxide emission through the thermal decomposition, and the leachate outlet to the water body or immigration to soil; and (ii) indirect vertical fluxes, consisting of carbon emissions from burning fossil fuel for collection, transportation, treatment and disposal of the MSW.

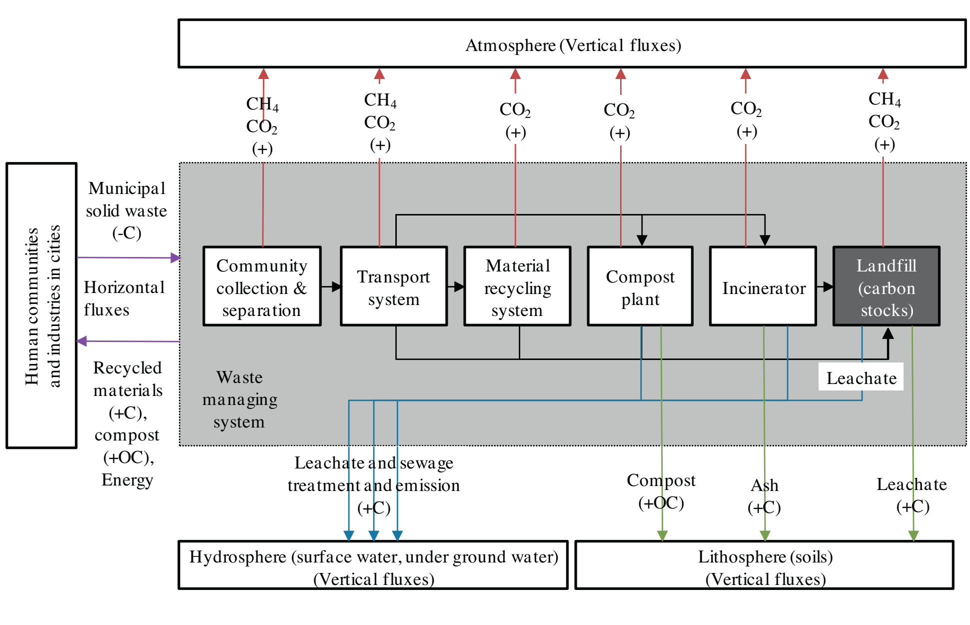


**Fig. 1.** Conceptual model of the carbon cycle of the municipal solid waste management system in terms of urban metabolism.