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A simulation model for methane emissions from landfills with interaction of vegetation and cover soil

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ABSTRACT

Global climate change and ecological problems brought about by greenhouse gas effect have become a severe threat to humanity in the 21st century. Vegetation plays an important role in methane (CH_4) transport, oxidation and emissions from municipal solid waste (MSW) landfills as it modifies the physical and chemical properties of the cover soil, and transports CH_4 to the atmosphere directly via their conduits, which are mainly aerenchymatous structures. In this study, a novel 2-D simulation CH_4 emission model was established, based on an interactive mechanism of cover soil and vegetation, to model CH_4 transport, oxidation and emissions in landfill cover soil. Results of the simulation model showed that the distribution of CH_4 concentration and emission fluxes displayed a significant difference between vegetated and non-vegetated areas. CH_4 emission flux was 1–2 orders of magnitude higher than bare areas in simulation conditions. Vegetation play a negative role in CH_4 emissions from landfill cover soil due to the strong CH_4 transport capacity even though vegetation also promotes CH_4 oxidation via changing properties of cover soil and emitting O_2 via root system. The model will be proposed to allow decision makers to reconsider the actual CH_4 emission from vegetated and non-vegetated covered landfills.

1. Introduction

Landfilling remains the primary treatment option for municipal solid waste (MSW) and other non-hazardous wastes in most parts of the world. Landfill gas (LFG, mainly CH_4 and CO_2) are produced during the stabilization process of MSW. Among of them, CH_4 is the most concerned as the second potent greenhouse gas (GHG) after CO_2 with a 21 times higher global warming potential than that of CO_2 over a 100-year period (IPCC, 2013). Following agriculture and coal mines, landfills are the third largest anthropogenic CH_4 emission sources. They were reported to emit about 138 million metric tons CO_2 equivalent ($MMTCO_2e$) in 2015 and accounted for about 17.7% of the USA CH_4 emissions (Chai et al., 2016). In 2030, emissions from landfills are expected to represent 10% of the global total methane from all sources (EPA, 2013). CH_4 is not only a greenhouse gas but also an energy reservoir, as it can be reused as a clean fuel or combusted for power generation or heat supply if an appropriate LFG collection system is in place (Aydi et al., 2015). Unfortunately, less than 50% of landfills have installed LFG collection system in China (Chai et al., 2016), and the collection efficiency varies from 8% to 90%, depending on the cover type (daily, intermediate and finally covers, with or without geomembrane), collection well type (horizontal or vertical well) and coverage (Börjesson et al., 2007; De la Cruz et al., 2016; Goldsmith et al., 2012; Spokas et al., 2006; Sun et al., 2015; Zhang et al., 2010). Consequently, a large amount of fugitive CH_4 is emitted to the atmosphere through daily and intermediate cover soil without geomembrane covered.

Due to the uncertainties and complexities association with the CH_4 production, consumption and transport process, the CH_4 emission flux in field landfills ranged over seven orders of magnitude from less than 0.0004 mg m^{-2} $d^{-1}$to more than 10,000 mg m^{-2} d^{-1}(Spokas et al., 2006). In some case, landfill can even be a sink for atmospheric CH_4 (Schuetz et al., 2003; Spokas et al., 2006). Compared with direct or indirectly measurement methods such as flux chamber, differential adsorption LiDAR, tracer dilution methods and stochastic search method (Abichou et al., 2006; Babilotte et al., 2010; Geck et al., 2016; Kormi et al., 2016; Taylor et al., 2016), the method of model, i.e., Intergovernmental Panel on Climate Change (IPCC) model, California Air Resources Board (CARB) model to predict CH_4 emissions from landfills is primarily applied due to the technological and economical limitation (De la Cruz et al., 2016). A few models have been established to assess the CH_4 transport and oxidation in landfill cover soil. Bogner et al. (1997) built a dynamic model for LFG transport and CH_4

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oxidation in landfill cover soils based on the mechanism of diffusion and convection. The model is attractive and innovative, but the CH_4 oxidation is modelled via the growth of bacteria on the surface of soil sphere by empirical equation instead of the factors influencing the growth of bacteria such as the water content, porosity and organic matters, thus the further validation of the model is limited for an unreliable predictive capacity for CH_4 oxidation in landfill cover soil. Some researchers used Fick's law and CH_4 oxidation kinetics to simulate CH_4 diffusion and oxidation in landfill soils (Bogner et al., 1997; Spokas et al., 2011; Stein et al., 2001). As the concentration of CO_2 in LFG can be as high as 40–50%(v/v) (Schuetz et al., 2003), Fick's law becomes unsuitable to analyze the LFG transport process as it only used in (i) binary mixtures, (ii) diffusion of dilute species in a multicomponent mixture (Webb and Pruess, 2003), and (iii) in the absence of electrostatic or centrifugal force field (Krishna and Wesselingh, 1997; Vural et al., 2010). Instead, the Maxwell-Stefan equation, a gas mixture diffusion equation, is more suitable to describe the LFG transport in landfill cover soils. De Visscher and Van Cleemput (2003) and Hilger et al. (1999) used the Maxwell-Stefan equation to simulate the LFG transport process. In the model of Hilger et al. (1999), O_2 is the only limiting substrate as the depth of methanotrophically active zone is limited by O_2 penetration, but it may lead to overestimate of CH_4 oxidation close to soil surface, where the concentration of CH_4 is low. The diffusion coefficients vary with the soil properties and climate conditions, the model built by Stein et al., 2001 and De Visscher and Van Cleemput (2003) applied concentration-dependent diffusion coefficients which improved the reliability and accuracy. Diffusion is usually viewed as the dominant transport mechanism in cover soil and convection can be negligible. However, continuous generation of LFG from the waste layer, temporal and spatial variability of meteorological conditions, and properties of the cover soil will nevertheless induce pressurization in the cover soil layer, and convection may thus also plays an important role in CH_4 transport(Park et al., 2016; Rannaud et al., 2009; Yao et al., 2015). A better understanding of CH_4 transport, oxidation and emission from landfill cover soils is needed to take proper measures to mitigate CH_4 emissions into the atmosphere.

After a landfill site has been closed, the surface of the cover soil will be covered by native plants (Xiaoli et al., 2011). Plants in the cover soil may have a positive influence on CH_4 oxidation as plants are reported to emit O_2 to the cover soil by spreading roots (Bohn et al., 2011; Colmer, 2003). Vegetation also alters the chemical and physical properties of the cover soil such as the density, moisture content and soil porosity. Furthermore, plant growth may provide nutrients and carbon source for methanotrophs by root exudates and debris of dead plants, thus improving CH_4 oxidation capacity (Bohn et al., 2011). However, certain plant species especially vascular plants may have a negative impact on CH_4 emission, as CH_4 may be released directly to the atmosphere through the aerenchyma (Rusch and Rennenberg, 1998).

The impact of vegetation on CH_4 transport, oxidation and emission has been modelled in rice paddies and wetlands (Li et al., 2016; Xu et al., 2007). The importance of vegetation in landfills, however, is not yet incorporated in landfill models. The CALMIM (California Landfill Methane Inventory Model) that incorporates both site-specific soil properties and soil microclimates based on 1-D diffusion is the most comprehensive model and validated in field landfills. In this model, vegetation coverage was included, but it mainly used to modify incoming solar radiation (Spokas et al., 2011); Abichou et al. (2015) modelled the effect of vegetation on CH_4 transport, oxidation and emissions in landfill across different climates. Their results suggest that the impact of vegetation on CH_4 oxidation and emission mainly works by changing the soil characteristics. They nevertheless neglected to incorporate the direct CH_4 transport by vegetation leaf stomata and stems (Rusch and Rennenberg, 1998).

The aim of this study is to develop a new simulation model that combines the multicomponent diffusive equation, convective equation and the dual Monod kinetic equation coupled with an embedded vegetation module to clarify the mechanisms of CH_4 transport, oxidation and emission in landfill soils covered with vegetation. The result of the simulation model will be proposed to allow decision makers to reconsider the actual CH_4 emission from vegetated and non-vegetated covered landfills.

2. Model description

The landfill cover soil is an unsaturated porous media. The LFG produced in the process of waste degradation is emitted to the atmosphere through the porous media by diffusion and convection, at the same time, part of CH_4 is oxidized during the process of transport by methanotrophs in the cover soil. The LFG transport and CH_4 oxidation are considered as the dominant processes governing CH_4 emission from the landfill cover soil. The multicomponent diffusive equation, Darcy's law and the dual Monod kinetic equation are the basic equations involved in the model (Fig. 1).

2.1. LFG diffusion model

Molecular diffusion of multicomponent gas mixture in unsaturated porous media is governed by the Maxwell-Stefan diffusive equation in landfill cover soil:

$$\frac{-P}{RT}\frac{\partial y_i}{\partial z} = \sum_{\substack{j=1 \\ k\neq i}}^{n} \frac{N_i y_k - N_k y_i}{D_{soil,ik}} \quad (1)$$

with $D_{soil,ij}$ the binary diffusion coefficient of a mixture of gases i and j in soil matrix ($m^2\ s^{-1}$), z the depth (z = 0 m at the soil surface), y_i the mole fraction of component i, P the absolute pressure (Pa), R the universal gas constant (8.3145 J mol^{-1} K^{-1}), N_i the flux of component i, i and k present the gas type (1-CH_4, 2-CO_2, 3-O_2, 4-N_2).

We used the Wilke approximation, a method of using Fick's law with variable diffusivities to solve Maxwell-Stefan diffusion:

$$j_i = -\left(\rho y_i \sum_k D_{soil,ik} d_k\right) \quad (2)$$

where j_i is the average flux of gas i (kg m^{-2} s^{-1}); ρ is the density of gas mixture (kg m^{-3}); d_k is the diffusive driving force of gas i (m^{-1}).

When the landfill gasses are in ideal state, then:

$$d_k = \nabla x_k + \frac{1}{P_A}[(x_k - y_k)\nabla P_A] \quad (3)$$

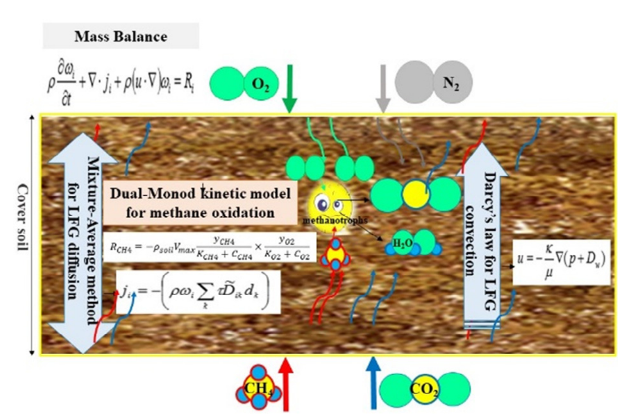

Fig. 1. The schematic diagram of the model.

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