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Comparison of first-order-decay modeled and actual field measured municipal solid waste landfill methane data

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ABSTRACT

The first-order decay (FOD) model is widely used to estimate landfill gas generation for emissions inventories, life cycle assessments, and regulation. The FOD model has inherent uncertainty due to underlying uncertainty in model parameters and a lack of opportunities to validate it with complete field-scale landfill data sets. The objectives of this paper were to estimate methane generation, fugitive methane emissions, and aggregated collection efficiency for landfills through a mass balance approach using the FOD model for gas generation coupled with literature values for cover-specific collection efficiency and methane oxidation. This study is unique and valuable because actual field data were used in comparison with modeled data. The magnitude and variation of emissions were estimated for three landfills using site-specific model parameters and gas collection data, and compared to vertical radial plume mapping emissions measurements. For the three landfills, the modeling approach slightly under-predicted measured emissions and over-estimated aggregated collection efficiency, but the two approaches yielded statistically equivalent uncertainties expressed as coefficients of variation. Sources of uncertainty include challenges in large-scale field measurement of emissions and spatial and temporal fluctuations in methane flow balance components (generated, collected, oxidized, and emitted methane). Additional publication of sets of field-scale measurement data and methane flow balance components will reduce the uncertainty in future estimates of fugitive emissions.

1. Introduction

Landfill disposal continues to be the most economically viable municipal solid waste (MSW) management practice in many countries, including the US; however, certain measures of control must be taken to minimize their environmental impact (Bogner et al., 2008). LFG is generated through decomposition of biodegradable landfilled material under anaerobic conditions and mainly consists of methane and carbon dioxide and smaller (<0.5%) amounts of non-methane organic compounds. In a typical engineered landfill, the fate of generated LFG changes over time. Initially, there is a period of time following waste placement and before landfill gas collection when landfill gas is emitted to the atmosphere unabated except for partial oxidation in soil covers. Once a gas collection system is installed, a fraction of the generated gas is collected through a network of wells and/or trenches maintained under negative pressure. However, even the most efficient gas control systems do not collect all of the LFG generated (Barlaz et al., 2009). Because of the high methane content, landfill gas (LFG) fugitive emissions are a major threat to the environment (Lizik et al., 2013; Abichou et al., 2011a,b; Jung et al., 2011).

Landfill methane emissions are driven by pressure (advection) and concentration (diffusion) gradients (Scheutz et al., 2009; Poulsen and Moldrup, 2006). Several temporally dependent parameters affect the advection mechanism, including cover permeability and moisture; dynamic viscosity driven by ambient and landfill cell temperatures; and pressure gradient controlled by atmospheric pressure, surface wind, and internal landfill pressure (Gebert and Grongroft, 2006; Poulsen et al., 2003; Abichou et al., 2011a,b). Atmospheric pressure and temperature typically vary diurnally (Gebert and Grongroft, 2006; Poulsen et al., 2001; Poulsen et al., 2003) and precipitation and wind vary more unpredictably (Poulsen and Moldrup, 2006; Gebert et al., 2011).

The efficiency of LFG collection systems depends on many factors including design and operation of the system; climate; and the composition, thickness, and integrity of the cover material. The fraction of LFG that is not collected may either move through the landfill cover soil where methane may undergo partial bio-oxidation or LFG may escape through preferential pathways (e.g., cap imperfections, LFG collection system leaks, or the leachate collection system). These two primary pathways persist after the shutdown

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of the LFG collection system, a situation that is allowable according to current US federal standards (USEPA, 1996). Research has shown that soil covers can be designed to promote methane oxidation and reduce fugitive emissions (Abichou et al., 2011a,b). The extent of methane oxidation is a function of methane loading rate, cover materials, cover thickness, quality and condition of the cover, and ambient temperature (Abichou et al., 2011a,b).

The extent of uncontrolled release of LFG is difficult to assess, although a number of methods have been developed to measure fugitive methane emissions. These include flux chambers, tracer gases, Horizontal Radial Plume Mapping Optical Remote Sensing (HRPM ORS), Vertical Radial Plume Mapping Optical Remote Sensing (VRPM ORS), inverse modeling, differential absorption light detection and ranging (LiDAR), micrometeorological eddy covariance (EC), and helicopter-borne spectroscopy (Babilotte et al., 2010). The flux chamber is the most common approach in LFG emission studies, mainly due to its simplicity and cost-effectiveness; however, the flux chamber has a small footprint and the measurements typically do not account for all emission sources. Other methods suffer from limitations such as uncertainty in source area, irregular topography, high cost and complexity, and/or sensitivity to atmospheric instability (Abichou et al., 2011a,b). The US EPA recommends using the VRPM ORS method (US EPA, 2007) to quantify fugitive methane emissions from landfills. Open-path optical remote sensing instrumentation measures path-integrated concentration along multiple paths. Meteorological data are combined with concentration measurements to calculate a mass emission flux from the source (US EPA, 2012).

Over the years a large number of numerical and mathematical models have been developed to estimate LFG based on zero, first, and second-order approaches. However, second-order models are not commonly used because the required parameters in each model are often so uncertain that they negatively affect the accuracy of the model outcomes (Tintner et al., 2012). Likewise, zero-order models do not reflect the biological LFG generation processes (Amini et al., 2011). Because of these limitations, simplified approaches have been developed based on first-order waste decay (FOD). The FOD model is widely used by industry, state regulators, the IPCC (IPCC, 2006) and the US EPA (US EPA, 2005) to estimate LFG generation. Most of these models are based on two primary model parameters, an ultimate methane generation potential and a first-order decay rate constant. A major challenge in modeling is estimating these parameters because they are affected by many factors including, among others, the amount of waste disposed, waste composition, moisture content, temperature, and lag time in gas generation. Consequently, results from models commonly used have large uncertainty; results vary from measured by 5–1109% (Amini et al., 2011). This uncertainty is compounded by the few opportunities to compare model results with large-scale landfill studies with complete data regarding the fate of generated methane (Oonk, 2010).

Accurately estimating the LFG generation, collection efficiency, and fugitive emissions assists landfill owners/operators in better understanding environmental impacts of landfilling and regulators in setting policies related to emission of greenhouse gases and other pollutants. Such information regarding methane generation and collection is essential when designing or evaluating LFG to energy processes. Also, insight on the variability of emission estimates should be incorporated into greenhouse gas inventories to increase their credibility and transparency. The objectives of this paper were to estimate methane generation, fugitive methane emissions, and aggregated collection efficiency through a mass balance approach using the FOD model for gas generation coupled with literature values for cover-specific collection efficiency and methane oxidation. This study is unique and valuable because actual field data from three US landfills were used for comparison to model results. These data included collected LFG and fugitive methane emissions measured using the VRPM ORS method for area source emissions (US EPA, 2012). Further, the variability in each component of a landfill methane flow balance derived from both modeling and field-measurement approaches was quantified and compared. This study may help to identify possible shortcomings in the continued reliance on the FOD model for both design and compliance purposes as well as the validity of literature reported values for methane collection and oxidation.

2. Methodology

To model methane flow components, a FOD gas generation equation was used and model parameters were estimated under site-specific conditions. Literature values for collection efficiency and methane oxidation as a function of landfill operating conditions were then applied to methane generation estimates to calculate methane collected and oxidized; emissions were estimated based on a volumetric flow balance. Modeled flow component values were compared to those derived from measurements of collected gas and emitted methane at three US landfills.

2.1. Case-study landfills

The three case-study landfills, described in more detail in US EPA (2012), were selected by the US EPA as sites with active LFG collection systems in all or parts of the landfills and representing various stages of landfill operation and closure. Details regarding site operating characteristics are provided in Table 1. The studied cell in **Landfill A** accepted waste from 1997 through 2006 within a 20-ha footprint closed with a mixed soil intermediate cover. An active LFG collection system was initially installed on Landfill A in 2007 and additional gas extraction wells were installed in 2010. The studied cell at **Landfill B** opened in 2000 and was operated as a traditional landfill until 2003 when leachate recirculation was initiated. Landfill B was closed partially with a geomembrane cover and partially with mixed soil at the time of this study. Active LFG extraction wells were installed at Landfill B in 2006, 2008, and 2010. **Landfill C** is an unlined cell that received waste between 1972 through 1997 and in a “piggyback” cell from 1997 to 2005. Landfill C was initially an unlined cell covered with an intermediate soil cover. An impermeable bottom liner was installed under the piggyback cell which was closed with a final geocomposite clay cap in 2005. LFG extraction wells were installed on Landfill C in 1997 and 2006.

2.2. Methane flow balance

With the assumption of a constant methane density, a mass balance for landfill methane can be expressed volumetrically as presented in Eq. (1). For longer periods of time, changes in landfill methane storage are generally assumed to be trivial in comparison to the other components, however, changes in storage can have a significant impact over shorter timeframes. In this study, methane storage is considered to be negligible. Each remaining component of the flow balance is described further below, along with a description of the approach for determining the component value and its variability.

$$Q_g = Q_{ox} + Q_{em} + Q_c + \Delta S \tag{1}$$

where Q_g is the generated methane, m^3 yr^{-1}, Q_{ox} is oxidized methane, m^3 yr^{-1}, Q_{em} is emitted methane, m^3 yr^{-1}, Q_c is collected methane, m^3 yr^{-1}, ΔS is the change in methane storage, m^3 yr^{-1}.