Waste Management 101 (2020) 28–34

Contents lists available at ScienceDirect

Waste Management

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

Estimates of methane emissions and comparison with gas mass burned in CDM action in a large landfill in Eastern Amazon

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ARTICLE INFO

Article history:
Received 30 November 2018
Revised 13 September 2019
Accepted 21 September 2019

Keywords:
Municipal solid waste
Greenhouse gas emission
Model retrieval

ABSTRACT

This work studied the methane gas production of the Aura landfill, the official destination of all Municipal Solid Waste of the Metropolitan Region of Belem (Brazil), operational until 2015. In 2007, the Aura Landfill was equipped with a landfill gas burning system in a CDM/UNFCCC project, with reported measured volumes of burned methane gas. These volumes were used to retrieve the methane generation potential (L_0) and the decay rate (k) parameters of single-phase, first order landfill emission model, yielding $L_0 = (61.0 \pm 6.6)\ m^3_{CH4}/Mg_{MSW}$ and $k = (0.25 \pm 0.07)\ yr^{-1}$. To model the Aura landfill, local gravimetric waste composition and local *per capita* waste production studies were collected, and the IPCC first order multiphase model was used. For the generation potential, observation and model are consistent, but for the decay rate, observations provide a 39% higher value, suggesting that the methane production from deposited MSW is occurring much faster than predicted by the IPCC model. Applying the retrieved parameters for the whole landfill's lifetime, the total produced methane is estimated to be 497 Gg (ranging from 444 Gg to 550 Gg), of this total 48% may have been emitted before the implementation of the collection system, indicating that it was implemented too late, and 81% may have been emitted before the closing date, with only 19% to be emitted after the end of operations. Subtracting the total methane volume burned in the CDM Activity, the Aura landfill may have emitted on total from 9.4 to 9.8 Tg of CO_2 equivalent.

1. Introduction

In the last decade, anthropogenic contributions to global methane emissions have been estimated to go from 48% to 78% of the total (Kirschke et al., 2013). Of these emissions, 6–14% are estimated to come from anthropogenic wastes (open dumps, landfills and sewage) (IPCC, 2007). In open dumps and landfills, the chemical composition of the landfill gas (LFG) generated by municipal solid waste (MSW) decomposition is basically CH_4 and CO_2, in an approximated proportion of 60% and 40% respectively (O'Leary and Tchobanoglous, 2002). The global warming potential of methane, when taking into account secondary effects, may well be much higher than the currently considered value of 25 times that of CO_2 (Shindell et al., 2009).

In Thailand, with a tropical equatorial climate, 78% of the solid waste disposal sites are open dumps (Chiemchaisri and Visvanathan, 2008). Emissions are much higher during the rainy season, the sharpest difference being in controlled landfills (Wangyao et al., 2010). In landfills in Florida, model adjustments to direct flux measurements indicate values for methane generation potential ranging from 56 m^3_{CH4}/Mg_{MSW} to 77 m^3_{CH4}/Mg_{MSW}, and for decay rate constant ranging from 0.04 yr^{-1} to 0.13 yr^{-1} (Amini et al., 2012).

In Brazil, estimation of methane production at the city of Rio de Janeiro's landfill are of about 57.4 m^3_{CH4}/Mg_{MSW} (Loureiro et al., 2013). At the Northeastern Brazilian city of Salvador, methane generation potential and decay rate estimates for sample measurements across nine years yielded 65.9 m^3_{CH4}/Mg_{MSW} and 0.21 yr^{-1} respectively (Machado et al., 2009). In the same region, detailed

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https://doi.org/10.1016/j.wasman.2019.09.029
0956-053X/

studies at Recife's main landfill showed the maximum methane production for new waste to be 31.8 kg_{CH4}/Mg_{MSW}/yr which after 18 months decreased to 8.85 kg_{CH4}/Mg_{MSW}/yr. Comparison with the IPCC model suggested using a larger generation rate than the model defaults, justified by the large hydric excess (annual rainfall of 2460 mm/yr with evaporation of 1390 mm/yr) in the region. (Maciel and Jucá, 2011; Maciel and Fernando Thomé Jucá, 2009).

Several models exist for estimating methane gas production generated in open dumps, controlled landfills and sanitary landfills (Kamalan et al., 2011), which can be either based on the underlying biochemical processes and are usually classified as zeroth, first, or higher order, or based on adjustable empirical functions whose coefficients are numerically adjusted to the emission data (Shariatmadari et al., 2007; Kamalan, 2016). Here we will consider only biochemically motivated models.

Estimates of methane emissions from landfills vary considerably among models, in some cases between five to seven times (Scharff and Jacobs, 2006). First-order multiphase models present the smallest errors compared to the measurement of methane flux rate (Oonk and Boom, 1995).

The Metropolitan Region of Belem (MRB), located on the eastern side of the Marajo Bay, has the highest population density in the Brazilian Amazon, and estimates of *per capita* waste production are scarce and range between 0.65 kg/day (ABRELPE, 2014) and 0.85 kg/day (GUAMÁ, 2016), which in 2010 (year of the last census) are equivalent to a production ranging from 468 and 612 thousand Mg per year. Such mass estimates are necessary as there are no direct measurements from the city's waste collection or disposal system.

The Aura landfill, located inside the MRB, at 1°25′S and 48°23′W, 13 km from the center of Belem, on the left banks of the Aura river and only 1.4 km of distance from the Bologna and Agua Preta lakes, the only metropolitan region's water reservoirs, is a mix of an open air dump and controlled landfill and was the destination of the entire MRB's MSW production between 1991 and 2015. As of 2006, it underwent the implementation of a Clean Development Mechanism (CDM) Action, of the United Nations Framework Convention on Climate Change (UNFCCC), for the collection and burning of methane produced, in order to capitalize on carbon credits (UNFCCC-CDM, 2017). Burned methane volumes where measured and may be used to estimate the methane production at the Aura Landfill.

Biogas collection system efficiency depends on landfill cover type and on details of the collection system. Compiled in Barlaz et al. (2009), collection efficiency values from studies in the USA and Sweden for landfills with thin clay, soil, and sludge covers vary from 33.9% to 70.0%, with mean value of $57.0\% \pm 12.7\%$. The USEPA's AP-42 draft report (USEPA, 2008) recommends an efficiency ranging from 50% to 95% with a 75% default value.

Correct estimates of methane production and emissions from MSW landfills are relevant to both environmental pollution studies and to power generation estimates. Estimates suggest that the power generation potential from MSW landfills in Brazil range from 523 to 768 MW (Lima et al., 2017).

The present work has three goals. First, to use the measured methane emitted masses from the CDM Action to fit a single-phase production model to estimate the generation potential (L_0) and the decay rate (k). Secondly, with this estimated model, point out that a large fraction of this landfill's methane emissions had already been emitted before the deployment of the gas collection system, and that most of the methane produced is generated before the closing date of the landfill. Finally, compare these estimates with IPCC's multiphase emission model (IPCC, 2006) adapted to the particular case of the Aura Landfill, and compare both to single-phase models like LandGEM (Alexander et al., 2005).

2. Model

Methane emission flux simulations from MSW landfills were performed using a first order multiphase model, defined by

$$Q_{CH_4}(t) = \sum_{i=1}^{N_t} Q_i(t), \tag{1a}$$

$$Q_i(t) = \sum_{p=1}^{N_p} M_{0i} f_p L_{0p} k_p e^{-k_p(t-t_{0i})} \theta(t - t_{0i}), \tag{1b}$$

where t_{0i} is the date of the i^{th} waste deposit, of mass M_{0i}, and N_t is the number of such deposit events. For the standard IPCC deposits happen yearly, and here (and in LandGEM) happen ten times per year. The flux generated at a time t by the i^{th} deposited mass is $Q_i(t)$, composed of a sum of N_p waste phases, with fractions f_p, methane generation potentials L_{0p}, and decay rates k_p. The step function $\theta(t - t_{0i})$ ensures that there is no flux before the deposit date. The total flux at a given time $Q_{CH_4}(t)$ is then the sum of all partial fluxes. The total generated methane mass is given by

$$M_{CH_4}^{tot} = \sum_{p=1}^{N_p} \sum_{i=1}^{Nt} M_{0i} f_p L_{0p}. \tag{2}$$

The values of k_i and L_{0i} used here were extracted from the IPCC model (IPCC, 2006), which defines L_0 as the product

$$L_0 = DOC \cdot DOC_f \cdot F \cdot MCF \cdot \frac{16}{12}, \tag{3}$$

where DOC is the fraction of the total mass made of Degradable Organic Carbon (here in kg_C/kg_{MSW}), here values given in (IPCC, 2006) for warm and humid tropical climate were used. Other parameters are constants given by the IPCC's recommended values: DOC fraction that decompose anaerobically - $DOC_f = 0.5$, Methane Correction Factor (fraction of DOC that survives degradation before the landfill reaches anaerobic conditions (Machado et al., 2009)) - $MCF = 0.8$ for deep controlled landfill, Fraction of anaerobically produced landfill gas consisting of methane - $F = 0.5$.

A simplification of the multiphase model in Eq. (1) is to consider $N_p = 1$, i.e. the MSW as being composed of a single amalgamated phase, with a single value for k and L_0. A popular single-phase model is LandGEM (Alexander et al., 2005). The relationship between methane generation potential between a multiphase model and a single-phase equivalent model is $L_0 = \sum_{p=1}^{N_p} f_p L_{0p}$, meaning that the total mass generated is the same. However, for the decay rate and instantaneous flux there is no direct simple equivalence between multiphase and single-phase models.

3. Waste production

3.1. Study location

The city of Belem, the capital of the state of Para, together with the neighboring municipalities of Ananindeua and Marituba, form the most populous part of MRB, covering an area of 1350 km^2 with a population estimated in 2017 of 2.09 million people (IBGE, 2017).

Between 2007 and 2017, the yearly mean precipitation was 2890 mm, the average monthly mean temperature was 26.8 °C (ranging from 21.4 °C to 35.5 °C), the mean relative humidity was 80.2% (ranging from 33.9% to 95.9%), and the average wind speed was 0.95 m/s (with mean maximum value of 5.62 m/s) (INMET, 2019).

Between 1991 and 2015, all the MSW collected in these three municipalities was deposited at the Aura Landfill, around which there are several low income residential neighborhoods.

During its lifetime, the Aura Landfill initially operated as an open sky dump (with waste being directly deposited over the bare ground and with no covering layer), then evolved to almost become a sanitary landfill for a few years (with an impermeable cover being placed over the waste pile and the implementation of the gas burning system), but eventually degraded to a controlled landfill (with a cover layer of earth periodically placed over the new waste) for the last 10 years of operation.

It was effectively closed for waste disposal in 2015. However, it is still the destination for non-residential inorganic residues and debris, as well as sporadic municipal gardening waste and septic tank sludge which have mass much smaller than the regular daily solid waste production and hence have been ignored.

3.2. Estimate of MSW mass produced in the MRB

Estimates of MSW collection in the MRB are scarce. Known Brazilian entities (IBGE, 2000; IPEA, 2012; ABRELPE, 2016) responsible for publishing such estimates produce hard to verify, amalgamated results, and local surveys are limited to master's theses. Direct measurements of MSW mass deposited at Aura Landfill were not cataloged in a consistent manner, and data provided by the Municipality of Belem through the Secretariat of Sanitation (SESAN), between 2002 and 2007, presented values that were inconsistent with other regional studies and inconsistent with population growth, and were not considered.

In Table 1 we have compiled the results of studies that present the daily *per capita* collected mass of non-industrial MSW at the MRB. All values are consistent, except for the value shown in IBGE (2000) which was discarded. Therefore the average value of *per capita* mass production used here were 0.74 kg/day, or 270 kg/yr. Total yearly population for the MRB were estimated by linearly interpolating data from three official population Census (for 1990, 2000 and 2007).

3.2.1. MSW gravimetric composition

To estimate waste composition, three studies (Carneiro, 2006; Lopes et al., 2004; GUAMÁ, 2016) on the gravimetric composition of the MRB's residential MSW were used, as presented in Table 2. They have been performed at different dates and with different levels of detail: Carneiro (2006) analyzed twenty-five 1-cubic meter solid waste samples from 10 different collection routes sampling various socioeconomic neighborhoods, GUAMÁ (2016) analyzed (in 2015) three solid waste samples from three economically distinct neighborhoods (total of 773 kg), and Lopes et al. (2004) presented no details besides the mean values for 1997.

For all categories except Organic Matter, Carneiro (2006) presents systematically higher fraction amounts than the other two studies, but this is due to the lack of classes "Textile", "Wood", and "Diapers".

The final fraction values used in the simulation performed here were the means of the three studies, where quantities not observed were taken to be zero. The IPCC model also presents estimates for the MSW fractions for the whole South American region(Table 2).

Table 1
Estimates for the Urban Solid Waste production in the MRB.

Year	Population (millions)	Collection kg/inhab/d	Source
1997	1.54	0.66	(Lopes et al., 2004)
2000	1.75	1.53	(IBGE, 2000)
2006	1.96	0.73	(Carneiro, 2006)
2012	2.01	0.78	(IPEA, 2012)
2016	2.08	0.80	(ABRELPE, 2016)
2006	-	0.71	IPCC Regional

4. Estimates

4.1. Observed methane flows and model parametrization

Starting in 2006, the United Nations Framework Convention on Climate Change (UNFCCC) approved a Clean Development Mechanism (CDM) Activity for the collection and burning of landfill gas produced by Aura Landfill, project number 888 (UNFCCC-CDM, 2017).

The gas collection system was implemented during a two year period (from 2007 to 2008) in two different ways. One consisted of a grid of vertical gas extraction wells spread across four cells (which were soon scheduled to stop receiving waste, according to direct conversation with the landfill's management in 2017). The other consisted of a network of horizontal perforated pipes, laid in 2-m deep trenches dug directly into the waste and lined with coconut refuse, spread across the remaining seven cells (some new cells, ready to receive new waste, some old, closed cells). Cover above the collecting system was either geomembrane or regular soil. Both wells and perforated pipes were connected by a network of non-perforated pipes to a centralized blower system to induce a vacuum. A secondary blower system was in stand-by in case of malfunction or inspection of the main system. Collected gas was then flared to convert methane into carbon dioxide, with reported efficiency values ranging from 90 to 99.99%. The CDM activity was officially planned to operate from April 30th, 2007 to April 29th, 2017. Actual reported gas collection and burning started on September 2007 and ended on February 2017, due to low gas collection rates.

Data presented in this CDM Action was the total daily LFG flow measured during the actual operating hours, the number of such hours in each day (usually less than 24 h), and the fraction of methane in the observed LFG. With this data a 24-h long total methane flow was estimated, assuming that the LFG flow rate would be the same also during the non-operating time intervals. These estimates were then summed to compute an estimated total monthly methane flow for each month of the CDM operation.

These methane flows are shown in Fig. 1 with gray dots and are labeled "CDM Data". Data start in 2007 and end in 2017, reaching maximum values between 2012 and 2015. Integration of this data estimate a total mass of generated methane during the whole burning operation to be 129.3 Gg_{CH4}. The actual measured mass, with the operational time gaps, was 120.9 Gg_{CH4}.

These observed flows are consistent with the produced methane observed at Recife's main landfill, which has similar waste composition and somewhat drier climate (Maciel and Jucá, 2011). Emission estimates at Recife varied from 31.8 to 8.85 kg_{CH4}/Mg_{MSW}/yr in a 18-month period. These values, when adapted to the 2-million people MRB, yield a flow ranging from 17 Gg yr^{-1} to 4.8 Gg yr^{-1}. This is consistent with the closing date emission maximum and the following descending part of the measured flows (Fig. 1).

These estimated total flow values were used to fit a single-phase model and retrieve optimal k and L_0 parameters, by minimizing the integrated squared residual

$$\chi^2(k, L_0) = \sum_{i=1}^{N} \left(M_i^{CH4} - \int_{t_{0i}}^{t_{1i}} Q(t; k, L_0) dt \right)^2, \tag{4}$$

where M_i^{CH4} is the observed mass of methane in a particular month (between instants t_{0i} and t_{1i}), N is the total number of months of data, and the integral over the model flux $Q(t; k, L_0)$ is the total methane mass generated in the same time interval.

As the landfill's management kept no records on cell usage dates, it was not possible to estimate the contribution of previously

Table 2
Waste composition studies performed in the MRB, values used in this study, and regional IPCC values. All amounts are wet basis.

Category	1997[a]	2006[b]	2015[c]	Used here	IPCC Regional
Org. Matter	58%	45.0	53.5%	52.2%	44.9%
Paper/Cardboard	14%	17.1	6.3%	12.5%	17.1%
Textile	4%	–	4.0%	4.0%	2.6%
Wood	1%	–	7.6%	4.3%	4.7%
Diapers	–	–	10.3%	3.4%	0.0%
Plastic	18%	15.3	9.8%	14.4%	10.8%
Metal	2%	2.9	2.1%	2.3%	2.9%
Glass	2%	1.9	0.8%	1.6%	5.7%
Other	1%	17.8[d]	5.6%[e]	8.1%	13.0%

[a] Lopes et al. (2004).
[b] Carneiro (2006) – Values are the average of 25 samples.
[c] GUAMÁ (2016) - Values are the average of 3 samples.
[d] Also includes textile, wood and diapers.
[e] Leather, dirt.

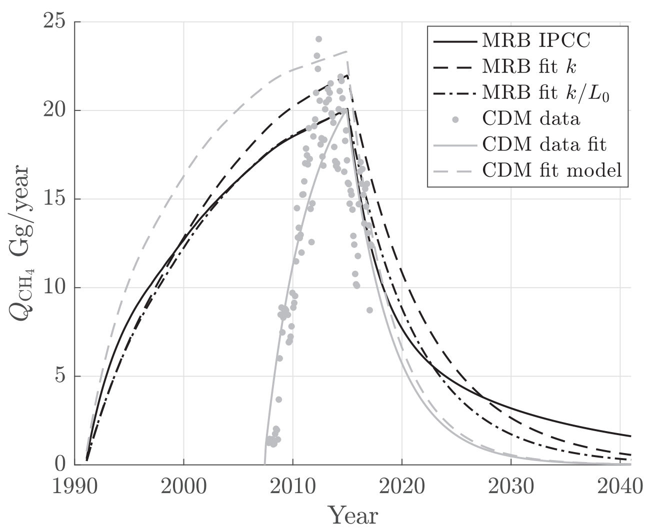

Fig. 1. Methane gas produced by the Aura landfill - actual CDM data and models.

existing waste to the collected LFG. However all new waste was deposited in cells already equipped with the collection system in place, and hence its emissions were collected. Therefore the possible contribution of old waste to the collected gas was taken to be zero and the observed flows were considered to represent emissions of MSW deposited only after 2007 Only this fraction of the total waste mass was considered in the simulations performed here.

No estimates of fugitive emissions were made during the system's operation, but field observations in early 2017 indicated clear presence of biogas in the air above the cells. As mentioned in the Introduction, these likely fugitive emissions could be in a wide range of values and therefore the retrieved values for the generation potential (L_0) and generated flux will represent a lower bound for the actual values. These values could be scaled up by using the inverse of the collection efficiency.

Values obtained in this retrieval, together with their 95% confidence intervals, for the generation potential was $L_0 = (61.0 \pm 6.6)\ m^3_{CH4}/Mg_{MSW}$ and for the decay rate was $k = (0.25 \pm 0.07)\ yr^{-1}$. The simulated methane generation time series based on these values is shown in Fig. 1 as "CDM Data Fit".

With these parameters in hand, and assuming their validity across time, a single-phase simulation was computed for the whole landfill's operation lifetime, starting in 1991, to estimate the landfill's total production. This is shown in Fig. 1 with line labeled "CDM Fit Model".

Based on this observation-based simulation, it was estimated that a total of (497 ± 53) Gg of methane was produce from 1991 the Aura landfill. Of this total, 48 ± 5% or (239 ± 47) Gg have been emmitted prior to the implementation of the gas burning system, 81 ± 5% or (404 ± 68) Gg have already been produced prior to the landfill closing date and 19 ± 5% or (93 ± 37) Gg are predicted to be generated after the closing date.

4.2. Multiphase estimation with IPCC model

To compare observations with theoretical predictions, estimates for the methane generated by the Aura Landfill were carried out using three versions of the IPCC model. The first was the multiphase IPCC model with phase fractions and MSW production adapted to the MRB as described in Section 3.2. The second was the single-phase version of the same model. These are called respectively "MRB" and "Bulk". Finally, a third multiphase simulation was performed but using IPCC's own regional estimates for *per capita* production (Table 1) and waste composition fractions (Table 2), and called "Regional". IPCC parameters used in these simulations are presented on Table 3, showing both DOC and k parameters for South America, with recommended values and possible range. The last row shows the single-phase model parameters.

Methane production estimated with these three models are presented on Fig. 2 showing how model results do heavily depend on the correct choices for DOC and k. The CDM fit model (Fig. 1) derived here fits in the upper range of IPCC's model parameters. The default IPCC Regional model follows closely the MRB model indicating that waste production and composition used here are consistent with regional averages.

4.2.1. Single-phase model fits

As the model used to fit observed emission data was a single-phase first order model, one way to compare observation with multiphase models is to estimate single-phase model parameters for all three IPCC models considered.

Given a multiphase model like IPCC's, $Q_{ipcc}(t)$, one can find a single-phase model best fit, $Q(t;k,L_0)$, by minimizing the integrated quadratic difference among such models:

$$\chi^2(k,L_0) = \int_0^\infty (Q(t;k,L_0) - Q_{ipcc}(t))^2 dt, \quad (5)$$

with respect to the variables k and/or L_0.

Best fits for both variables using the "MRB" run yield $k = 0.18\ yr^{-1}$ and $L_0 = 53.3\ m^3_{CH4}/Mg_{MSW}$. For comparison, another fit was performed by keeping L_0 fixed to the theoretical value of $L_0 = \sum_i f_i L_{0i} = 59.6\ m^3_{CH4}/Mg_{MSW}$, and with this constraint, k is adjusted to $0.16 yr^{-1}$. These fits are called "MRB fit k/L_0" and

Table 3
South America's IPCC's values for DOC and k used in the simulations used here. Range values are the adopted minimum and maximum. From (IPCC, 2006).

Phase	DOC (fraction)		k (yr^{-1})	
	used	range	used	range
Food	0.15	0.08–0.20	0.4	0.17–0.7
Garden	0.20	0.18–0.22	0.17	0.15–0.2
Paper	0.40	0.36–0.45	0.07	0.06–0.085
Wood	0.43	0.39–0.46	0.035	0.03–0.05
Textile	0.24	0.20–0.40	0.07	0.06–0.085
Nappies	0.24	0.18–0.32	0.17	0.15–0.2
Sewage	0.05	0.04–0.05	0.4	0.17–0.7
Rubber	0.39	0.39–0.39	0.035	0.03–0.05
Bulk	0.16	0.12–0.28	0.17	0.15–0.20

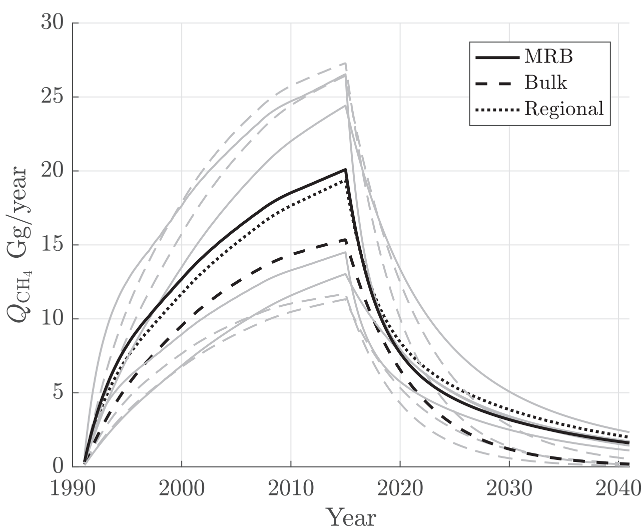

Fig. 2. Variability in range of methane gas production based on the IPCC model for the Aura landfill. Here dark lines show modeling with the recommended set of parameters, and gray lines show the spread of the results when using the given range of values for both DOC and k. Solid lines represent the "MRB" run, dashed lines the "Bulk" run, and the dotted line, the "Regional" run.

Table 4
Values of k and L_0 for the single-phase models used here.

	L_0 m^3_{CH4}/Mg_{MSW}	k yr^{-1}
CDM Data Fit	61.0±6.6	0.25±0.07
MRB fit k	60	0.16
MRB fit k & L_0	53	0.18
Bulk	42	0.17
LandGEM C.A.A.	156	0.05
LandGEM Conv. Inv.	92	0.04
LandGEM Humid Inv.	88	0.07

"MRB fit k" respectively. The same procedure was done for the "Bulk" run, yielding $k = 0.17\ yr^{-1}$ and $L_0 = 41.9\ m^3_{CH4}/Mg_{MSW}$.

4.3. Result comparisons

Observation-based retrievals for k and L_0 as well as estimated values for the three IPCC model variants considered here are presented on Table 4. The retrieved L_0 value was larger than IPCC's multiphase total L_0 ("MRB fit k") by only 1.8% (although with 95% confidence interval ranging from −22% to 12%). However, comparison with the other two fits indicates that the observed L_0 is always larger than IPCC's estimates by up to 45%. Similarly for the decay rate, the observed k value is consistently larger than the IPCC's estimated values by between 39% and 56%.

For comparison, also shown in Table 4, are the standard values for k and L_0 taken from the LandGEM model: "Clean Air Act", "Conventional Inventories" and "Moist Inventories". Here it is shown that in all cases LandGEM uses values for L_0 between two and four times greater than the estimations from the multiphase IPCC model, leading to an overestimate of 100% and 300% for the total CH_4 generated. Also values for k are a factor of two to four times smaller, thus estimating a slower methane production from the MSW. In the case of the "Wet Inventory", in principle the most similar to this study case, it uses 45% higher generation and a 39% lower decay rate. This indicated that the use of the LandGEM model, as presented by the EPA, is not adequate for the estimation of emissions in other regions.

For further comparison, it has been also included on Fig. 1 the "MRB IPCC" run (solid black line), and its both first order fits, "MRB fit k" (dashed black line) and the "MRB fit k/L_0" (dash-dotted black like). The "CDM fit model" presented higher emission rates during the active life of the landfill and a considerable lower flux after the landfill closure. This is because the retrieved decay rate (k) is considerably higher than in the IPCC model, for a roughly similar generation potential.

Finally, total produced methane amounts over the operational lifetime of the landfill, up to the implementation of the gas collection systems, up to the closure date in 2015, and after the closure date, are summarized on Table 5. Each row represents one of the models considered here.

The total generated methane masses for both CDM Data Fit and IPCC MRB models differ by only 2.5% (for the central value), showing consistency among the IPCC model and the direct observations, also indicated by the L_0 values on Table 4.

Fractions of the total released emissions as a function of time differ among models. From 1991 to 2008, the CDM Data Fit model indicates that 48% of the total methane had already been emitted, contrasting with the IPCC MRB model value of $39 \pm 7\%$. At the landfill's closing date, the methane fraction of the total produced was 81% for the CDM Data Fit model, and $66 \pm 10\%$ for the MRB IPCC. Finally, the fraction of the total methane generated after the landfill's closing date is only 19% for the CDM Data Fit model but $33 \pm 4\%$ for the MRB IPCC model.

Table 5
Estimated total methane production and variability range for the Aura landfill.

Type	Total	Up to 2008	Up to 2015	After 2015
CDM Data Fit	497^{444}_{550} Gg	239^{190}_{284} Gg	404^{332}_{468} Gg	93^{66}_{139} Gg
IPCC MRB	484^{338}_{606} Gg	192^{103}_{275} Gg	333^{186}_{459} Gg	151^{107}_{239} Gg
IPCC*Bulk*	341^{255}_{596} Gg	141^{100}_{261} Gg	249^{179}_{456} Gg	92^{60}_{179} Gg
IPCC Regional	497 Gg	178 Gg	311 Gg	186 Gg
MRB fit k	486 Gg	190 Gg	345 Gg	141 Gg
MRB fit k/L_0	434 Gg	182 Gg	323 Gg	112 Gg

Superscripts and subscripts on the main number indicate the maximum and minimum estimated emitted values respectively.

5. Conclusion

Methane emission models for MSW landfills are essential for estimating their impact on air quality and on greenhouse gas inventories. However, to obtain realistic results, the choice of model parameters should be judicious, depending on the particularities of the landfill in question.

Here, a comparison was made between observed methane emission data collected by the UNFCCC Action 888, and the IPCC multiphase model together with three single-phase variants.

The application of the IPCC multiphase model to Aura Landfill estimates a total methane emission of 484 Gg, where 69% occurs during the period of activity and 31% after its closure. This result compares well the values simulated by the Regional IPCC models (497 Gg, 63% and 37%), where no particular information is provided except population.

Comparing the multiphase IPCC MRB model with all three single-phase variants (*Bulk*, and fits), single-phase models consistently show a small overestimation of emitted methane over the period of active operation (from 66% to 73% on average of models considered here), and a small underestimation after the closing year (from 34% to 27% on average).

The use of the data measured by UNFCCC CDM Action 888 allowed for the estimation of single-phase model parameters to be $L_0 = (61.0 \pm 6.6)\ \mathrm{m}^3_{\mathrm{CH4}}/\mathrm{Mg}_{\mathrm{MSW}}$ and $k = (0.25 \pm 0.07)\ \mathrm{yr}^{-1}$. The value of L_0 here differing only 1.4% from IPCC's fit value, where k is considerably larger (from 39% to 56%), and with between 75% and 85% of the emissions occurred before the landfill was closed.

Although the methane burning system implemented at the Aura landfill was operational for almost 10 years and burned about 120 Gg of methane, the data modeling done here suggests that it was implemented too late. Before the system's implementation, the CDM Data Fit model estimates that from 43% to 52% of the total methane emissions would have already been release prior to 2008.

In comparison, the LandGEM model, commonly used for modeling (as was done in Action 888), uses very different values for both L_0 and k when compared to the adjusted values from the observed data or the IPCC. This indicates that landfills in hot and humid tropical regions are not directly modeled with the U.S. LandGEM default parameters.

For the example presented here, of a large landfill in the Amazon, values for k are higher than usual. This suggests that the application of emission control methods in the Amazon must be carried out early in the operation lifetime, to limit the amount of produced biogas released to the atmosphere.

Most of the Aura greenhouse gas emissions have already occurred. Even with the burning of 120 Gg of collected methane, total methane emissions for the whole lifetime of the landfill would be between 364 Gg (IPCC MRB) and 377 Gg (CDM Data Fit), of which more than 81% have already been released. Considering the global warming potential of CH_4 to be at least 25, the Aura Landfill has emitted on total, over the years, approximately 9.4–9.8 Tg of CO_2 equivalent.

Acknowledgments

This work has been supported in part by the Brazilian Ministry of Labor under the project "Incubação para fortalecimento de cooperativas e associações de catadores e catadoras de materiais recicláveis e reutilizáveis em Municïpios do Pará" executed by the Universidade Federal do Pará, Brazil.

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