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A Greenhouse Gas Inventory in the Municipal Landfill of the City of Limeira, Brazil

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Landfill main gases are methane and carbon dioxide, and result mainly from the anaerobic digestion of organic waste. The exact distribution of gases in the landfill varies with the landfill age among other factors such as waste composition, moisture, particle size, temperature, pH, age of waste, landfill design and operation. The current Brazilian environmental legislation has encouraged the municipalities to adopt measures to reduce greenhouse gas (GHG) emissions from landfills. The implementation of projects to reduce GHG requires the estimation of the gases produced in the landfill. This research presents a GHG inventory performed in the landfill of the city of Limeira, located in the State of Sao Paulo, Brazil. The inventory was conducted by using the Brazilian GHG Protocol that follows the methodology of the Intergovernmental Panel on Climate Change (IPCC), and also IPCC guidelines. The inventory comprised data from 1985 to 2013; however, data prior to 2000 were estimated, because until that year the landfill was in fact a dump, with no monitoring of the amounts of wastes disposed of. Three categories of emissions were considered: a) direct emissions of CO_2 and CH_4 from the decomposition of municipal solid waste (MSW) and non-hazardous industrial waste and the emissions produced from waste transportation within the landfill and landfill operation; b) emissions resulting from electricity consumption within the operating limits of the landfill; and, c) indirect emissions from waste transportation throughout the city to the landfill and also from industries to the landfill. The results showed that in the year 2013 were emitted 35,996.91 t of CO_2 e into the atmosphere. From the total, 98.91 % of emissions were produced by MSW decomposition; 0.002 % by industrial waste decomposition; 0.332 % by burning fossil fuels during landfill operation; 0.003 % by electricity consumption of electricity in the landfill and 0.75 % by waste transportation.

1. Introduction

An increase in industrial production, population and urbanization increases the consumption of goods and services and results in increased solid waste generation, particularly in urban areas in which waste includes public and household solid waste and is called municipal solid waste (MSW). The most common method for treating and disposing of MSW in Brazil has been waste disposal on the ground, which can include inappropriate disposal methods (such as dumps), or disposal in landfills. The latter utilize methods for the treatment and final disposal of MSW according to project and operation guidelines based on engineering criteria (Barros et al., 2014).

Brazilian population in 2013 comprised 201,062,789 inhabitants, and in the same year an average of 209.280 t/day of MSW was produced, which means a per capita generation rate of 1.041 kg/capita/day. From the MSW produced in 2013, 58.3 % was correctly disposed in landfills and 41.7 % was sent to dumps, according to the Brazilian Association of Public Cleaning Companies and Special Wastes (ABRELPE, 2013). In order to solve this problem, the National Solid Waste Policy (NSWP), created in 2010 established that by August 2014 all municipalities should extinguish their dumps. However, this goal has not been reached yet, and the deadline for the closure of dumps was delayed until August 2016.

Thus, even though the global environmental legislation and even NSWP drive to the adoption of more efficient technologies for MSW disposal, such as composting or waste to energy facilities, in Brazil this reality seems

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somewhat distant. A first step for MSW in Brazil is the closure of existing landfills across the country, and for that reason, it is expected that the landfilling will remain as the main technology for MSW destination for years. As stated by Fodor and Klemeš (2011), landfills have the advantage of being a technology of relatively low cost and easy to implement, complement with other technology options for handling residual waste, and can derive landfill gas (LFG) as a by-product for household and industrial uses. As disadvantages the authors state that landfills demand large land areas, have the cost incurred as landfill expand, do not reduce MSW volume, result secondary pollution problems (as groundwater and air pollution and soil contamination); and, due to public resistance and space limitation, landfills are often far away, resulting in long distance transport.
Considering the MSW practices currently adopted by most of municipalities in Brazil, and also that the household waste has in its composition an average of 55 % of organic matter, the LFG recovery as a source of energy is highly recommended.
Barros et al (2014) have studied the electric energy potential of LFG in Brazil. The study was divided into two phases: (1) examined scenarios encompassing five possible population sizes contributing to landfills for the generation of electricity in Brazil; (2) the contribution of the energy generation potential from LFG, based on the population size given in phase 1 was evaluated by comparing it to Brazil's main energy plant and energy expansion plans, based on economic expansion scenarios. The results of the simulations showed that initiatives for energy generation plants using LFG became financially attractive for populations with more than 200,000 inhabitants. Also, the results demonstrated that such values still represented a small percentage (0.00020 % in 2010 and 0.44496 – 0.81042 % in 2030) of the projected energy generation from residual fuels. Thus, the authors have identified an urgent need to formulate policies that would encourage landfills as a source of renewable energy, broadening the number of financially viable initiatives for energy generation from landfill biogas for populations of fewer than 200,000 inhabitants.
In this scenario, this study conducted an inventory of GHG emissions in the municipal landfill of Limeira, a medium-sized city in the State of Sao Paulo, Brazil. The main objective of the study was to estimate the generation of GHG related to solid waste management in the municipality, identifying the main sources of methane generation and its potential for recovery and use as an alternative energy source.

2. Methodology

This section presents the methodology adopted in this work. Section 2.1 details the region of study and where the data considered in this work were collected, while section 2.2 shows details about the Protocol adopted to calculate the inventory.

2.1 General site description and data collection

The Limeira City Municipal Landfill, where the GHG inventory was performed, is located in the Southeast region of Brazil, and is distant 9 km from the city downtown area. Its geographical location is 22°37´59´´S, 47°21´45´´W and height is 598 m (Figure 1). This area, called "Landfill Complex", is in operation since 1985 and is divided into three sections: Stage I (reached its final storage capacity in 1995 and was closed); Stage IIA (used until December 2012, when was also closed) and Stage IIB (established in February 2013, with an expected useful life of 30 months, which ends in December 2015).
Municipal solid waste (MSW) collection covers approximately 100 % of the urban area; mixed wastes delivered by population in containers located in the streets are collected by a private company every day are and sent to the landfill (Limeira, 2014a). The municipal landfill has also an official permission to dispose of non-hazardous industrial wastes along with the MSW, in the same cell. Thus, the cell currently in operation receives MSW (both organic and recyclables, since the waste sorting system is not efficient), waste from pruning activities and non-hazardous industrial waste. Those wastes are disposed in the cell, compacted and covered with soil. The mine from where the cover soil is extracted is distance 1 km from the landfill. The landfill cell was projected and operated according to the Brazilian Non-Hazardous Waste Landfill Standards, and has a total capacity of $1x10^6$ t of waste (Limeira, 2014b).
The GHG inventory was performed by using data from 1985 to 2013; the municipality of Limeira provided the data from 2000 to 2013 and other important information regarding to waste transportation and landfill operation. Additional data, from 1985 to 2000, were estimated.

2.2 The inventory of GHG emission methodology

The inventory was performed by using the Brazilian GHG Protocol that follows the methodology of the Intergovernmental Panel on Climate Change (IPCC), and IPCC guidelines. The Brazilian GHG Protocol (GHG Protocol Brazil, 2013) provides a tool to calculate GHG emissions, which consists of an excel spreadsheet. Three categories of emissions considered in this study were: Scope 1 (direct emissions of GHG); Scope 2 (indirect emissions of GHG from energy) and Scope 3 (other indirect emissions) (GHG Protocol, 2012).

Figure 1: Landfill localization with cells in details (Adapted from Google Earth, 2014).

2.2.1. Scope 1

Scope 1 represents the CO_2 and CH_4 emissions from the decomposition of MSW and non-hazardous industrial waste in the landfill, and also, the emissions produced by waste transportation within the landfill and landfill operation. To calculate these emissions, the GHG Protocol tool requires the following data: the total amount of waste landfilled within the considered period of time, as well as the waste composition; average of temperature and precipitation rates; methane correction factor (MCF) and the oxidation factor (OX).of the disposal site; and, the methane concentration and recovery rate.

As historic data of waste disposal has been recorded only after 2000, it was necessary to estimate the amount of MSW sent to the landfill from 1985 to 2000. This estimative was performed by considering the number of inhabitants in each year and the correspondent average rate of waste generation (t/capita/y), according to data from São Paulo State Environmental Agency (CETESB, 2013), and resulted in a total amount of 1,447,067 t of MSW over the period.

Regarding to the MSW composition, it was considered only data from paper/cardboard, food scraps and inert materials, which are the main compounds present in the solid waste flow that is delivered in the landfill.

Data from precipitation and temperature were used for selecting the methane generation factor according to the composition of waste. The values for these parameters are available in EMBRAPA (2014): the annual average ambient temperature is 21.1 °C and the annual rainfall is 113 mm. According to IPCC (2006), the recommended default methane generation rate (that is a dimensionless number)considering the average of temperature and rainfall rates is: 0.04 for paper/cardboard; 0.024 for textile waste; 0.015 for food scraps; 0.043 for wood; 0.02 for garden waste; 0.024 for diapers; and, 0.039 for rubber and leather. The particular characteristics of the landfill must be considered to define the methane correction factor (MCF) and the oxidation factor (OX). The MCF accounts for the fact that unmanaged solid waste disposal sites produce less CH_4 from a given amount of waste than the anaerobic ones. In unmanaged landfills, a larger fraction of waste decomposes aerobically in the top layer, and in unmanaged landfills with deep disposal and/or with high water table, the fraction of waste that degrades aerobically should be smaller than in the shallow ones. Semi-aerobic landfills are managed passively to introduce air to the waste layer to create a semi-aerobic environment within the cell. The MCF in relation to solid waste management is specific to that area and should be interpreted as the waste management correction factor that reflects the management aspect it encompasses. The oxidation factor (OX) reflects the amount of CH_4 from the landfill that is oxidised in the soil or other covering material. Studies show that sanitary, well-managed landfills tend to have higher oxidation rates than unmanaged dump sites. The oxidation factor at sites covered with thick and well-aerated material may differ significantly from sites with no cover or where large amounts of CH_4 can escape through cracks/fissures in the cover. A default

value of these parameters is provided for countries where the quantity of waste disposed to each site is not known. Table 1 shows MCF and OX factors according to the different types of disposal sites (IPCC, 2006).
Considering the characteristics of the Limeira's Municipal Landfill, we have adopted the default values for MCF and OX factors corresponding to a "uncategorised site" from 1985 to 2000 (0.6 and 0.0 respectively) and to a " managed – semi-aerobic site" from 2000 to 2013 (0.5 and 0.0 respectively).

Table 1: Disposal sites classification and methane correction factors (IPCC, 2006).

Types of site	Default values	
	MCF	OX
Managed – anaerobic	1.0	0.1
Managed – semi-aerobic	0.5	0.0
Unmanaged – deep (> 5 m waste) and/or high water table	0.8	0.0
Unmanaged – shallow (< 5 m waste)	0.4	0.0
Uncategorised	0.6	0.0

The gases produced in the landfill are drained through a piping system to the atmosphere, without any device for controlled burning or gas recovery. Then, there are no data regarding to the methane composition and recovery rates. For that reason, it was adopted the default value of 0.5 for methane concentration, as suggested by IPCC (2006).
For the GHG emissions from industrial waste we used almost all the same data used to calculate GHG emissions from MSW. The only different data considered were the quantities and the composition of industrial waste. These data were provided by the municipality and amount approximately 380,510.7 t of wastes disposed of in the landfill over the period between 1985 and 2000, which composition is shown in Table 2. Data before 2000 were not available, because industrial waste has not been disposed in the landfill.

Table 2: Industrial waste composition disposed in the landfill (2000-2013).

year	paper and cardboard (%)	textile waste (%)	food waste (%)	wood (%)	garden waste (%)	diapers (%)	rubber and leather (%)	other inert materials (%)
2000	-	2.99	0.54	-	-	-	-	96.47
2001	0.21	-	0.05	0.006	-	-	0.025	99.70
2002	0.43	0.11	-	-	-	-	0.500	98.96
2003	7.48	0.01	-	-	-	-	-	92.50
2004	23.86	0.40	-	-	-	-	-	75.74
2005	-	0.22	-	-	-	-	-	99.97
2006	-	0.22	-	-	-	-	-	99.77
2007	-	-	-	-	-	-	3.490	96.50
2008	6.96	-	-	-	-	-	-	93.03
2009	-	-	3.52	0.430	-	-	0.070	95.98
2010	-	-	-	-	-	-	-	100.00
2011	-	-	-	-	-	-	-	100.00
2012	-	-	-	-	-	-	-	100.00
2013	-	-	-	-	-	-	-	100.00

The GHG emissions resulting from the landfill operation comprises the emissions produced by three tractors. Each tractor consumes an average of 300 L of diesel fuel per week, which means an annual average consumption of 43,200 L. To calculate the emissions it was used the methodology "top-down", in which the Eq. 1 gives the unit conversion, Eq. 2 gives the amount of carbon emitted by the fuel, and Eq. 3 gives the CO_2 emission.

$$\mathrm{CC} = \mathrm{CA} * \mathrm{Fconv} * 45{,}2 * 10^{-3} * \mathrm{Fcorr} \quad (1)$$

Where:
CC = energy consumption (TJ);
CA = fuel consumption (m^3);
Fconv = conversion factor of fuel consumption for tons of oil equivalent (tEP); for the diesel fuel this factor is equal to 0.848 (tEP/m^3);
Fcorr = correction factor of the high heat value (PCS) to lower calorific value (PCI); for solid and liquid fuels this factor is equal to 0.95.

$$QC = CC * Femiss * 10^{-3} \quad (2)$$

Where:
QC = carbon content (Gg);
CC = energy consumption (TJ);
Femiss = carbon emission factor (tC/TJ); for diesel fuel this value is 20.2 tC/TJ.

$$ECO_2 = EC * 44/12 \quad (3)$$

Where:
ECO_2 = CO_2 emission (Gg);
EC = carbon emission.

2.2.2. Scope 2
In this scope, we have calculated the GHG emission produced due to the energy consumption in the landfill activities (Eq. 4), according to data provided by the municipality (Table 3).

$$CO_2E = EC \times EF \quad (4)$$

Where:
EC = electricity consumption (MWh);
EF = emission factor (tCO_2e/MWh); In Brazil, the main source of energy is hydraulic, and for that reason we adopted EF = 0.0960 tCO_2 / MWh.

Table 3: Energy consumption in the landfill in 2013 (kW).

month	Jan	Feb	Mar	Apr	Mai	Jun	Jul	Ago	Sep	Oct	Nov	Dec	Total
energy consumption (kW)	960	832	1,282	1,045	847	1,054	948	784	989	604	1,156	836	11,337

2.2.3. Scope 3
This scenario represents the indirect emissions from waste transportation throughout the city to the landfill and also from the industry sites to the landfill. Table 4 shows the estimated average distance from the different regions of the city to the landfill, and the diesel fuel consumption by the vehicles used to the MSW and industrial waste transport.

Table 4: Distance and diesel consumption from waste transport.

Vehicle	Distance (km/month)	Diesel consumption (L)
Compactor truck	21,743	3,911
Truck (6 m^3)	988	312
Truck (5 m^3)	1,482	468
Truck (10 m^3)	19,410	3,491
Truck (15 m^3)	6,365	1,145
Particular vehicle	2,755	344
Total	52,743	9,671

3. Results and Discussion

The values obtained in the calculations performed in the three scopes presented in the previous section, allowed us to estimate the total GHG emissions. The result value obtained was 35,996.91 t of CO_2e emitted into the atmosphere in 2013. Table 5 shows the GHG emission for each scope.

Table 5: Total GHG emissions by the landfill in 2013.

	Source	GHG emission (tCO_2e / year)	GHG emission (%)
Scope 1	MSW	35,604.590	98.912
	industrial and inert waste	0.869	0.002
Scope 2	energy consumption	1.088	0.003
Scope 3	transportation	390.000	1.083
	Total	35,996.547	100

As may be seen, the main source of GHG emission in Limeira's landfill is the MSW disposal, due to the fact that this category represents the largest amount of waste disposed of in the landfill since 1985. Still, the MSW in Brazil, in mid-size cities, has an average content of approximately 55 % of organic matter, which may produce gases by anaerobic decomposition by up to 30 years after its disposal in landfill. As the landfill does not have a burning system for the gases, they have been sent directly to the atmosphere, contributing for the increasing rate of global warming. It is important to emphasize that a similar situation happens in most small and midsize Brazilian municipalities. Only the large sanitary landfills in the country have efficient systems that capture, treat and recover the gases.

4. Conclusions

The GHG inventories indicate which sector of a company or institution emits more greenhouse gases into the atmosphere, enabling users of this tool to define emission reduction policies and improve their processes and/or their technologies. Considering the environmental importance of de landfill gases, regarding to their contribution to GHG emissions, and the need for decentralized electricity generation close to urban areas in Brazil, the results of this study highlighted the need for the implementation of public policies to support those initiatives.

The results of this study call the attention to the need for improvements in the solid waste management system in the city of Limeira as a whole. First, it should be invested in MSW collection and diversion systems, as a great amount of recyclable materials arrive at the landfill. Second, decentralized composting systems could be designed for treating the food scraps, which represent the largest source of materials with potential for generation of GHG. And third, the municipality should improve the landfill gases collection system, so that the gases would be captured more efficiently and also be monitored. By having more accurate data concerning the gases flow rate and composition, feasibility studies on recovery GHG for use as an energy source could be done.

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