Vol. 60, p. 357-373, jul./dez. 2022. DOI: 10.5380/dma.v60i0.71476 e-ISSN 2176-9109

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Methane emissions and carbon storage from household paper disposal in Brazil during 1901-2016

Emissões de metano e estocagem de carbono por disposição de papéis domésticos no Brasil entre 1901 e 2016

Carlos Roberto SANQUETTA[1*], Ana Paula DALLA CORTE[1], Mateus Niroh Inoue SANQUETTA[1], Greyce Charllyne Benedet MAAS[1], Margarida TOMÉ[1]

[1] Universidade Federal do Paraná (UFPR), Curitiba, PR, Brasil.

[*] E-mail of contact: sanquetta@ufpr.br

Article received on October 5, 2020, final version accepted on March 7, 2022, published on september, 26, 2022.

ABSTRACT: In this paper, we estimated the methane emissions by the disposal of sanitary and domestic-use paper consumed throughout Brazil from 1901 to 2016. The apparent consumption of this type of paper from 1961 to 2016, calculated from the data of the FAOSTAT system, was used to estimate the amount of waste disposed of annually in three site categories: sanitary landfill, controlled dump, and open-air, uncontrolled dump. The 2006 IPCC Guide methodology was used to calculate CH_4 emissions and long-term carbon storage. Nine scenarios based upon the law that establishes the National Solid Waste Policy (NSWP) were examined, considering 100% waste disposal and treatment in landfills or incineration from 2014. The total emission was estimated at 1.967 $MtCH_4$, corresponding to 55.080 $MtCO_{2eq}$ by GWP-AR5, and the stored carbon at 3.724 Mt, corresponding to 13.655 $MtCO_{2eq}$. CH4emission increased beyond the population growth rate due to an increase in the per capita paper consumption in the country, from 0.02 $kgCH_4.year^{-1}$ in 1961 to 0.30 kg $CH_4.year^{-1}$ in 2016. The NSWP has not yet been accomplished, and the scenarios outlined indicate that, from the point of view of CH_4 emissions, it would be more advantageous to carry out incineration instead of applying other waste treatment technologies.

Keywords: decomposition; climate change; forest products; toilet paper; waste.

RESUMO: Neste artigo, nós estimamos as emissões de metano pela disposição final de papel sanitário e de uso doméstico consumido em todo o Brasil durante o período de 1901 a 2016. O consumo aparente desse tipo de papel durante 1961-2016, calculado a partir dos dados do sistema FAOSTAT, foi usado para estimar a quantidade de resíduos disposta anualmente em três tipos de destinação: aterro sanitário, aterro controlado e lixão a céu aberto. A metodologia do Guia do IPCC de 2006 foi usada para calcular as emissões de CH_4 e o armazenamento de carbono a longo prazo. Foram analisados nove cenários baseados na lei que estabelece a

Política Nacional de Resíduos Sólidos (PNRS), considerando 100% de disposição e tratamento de resíduos em aterros ou incineração a partir de 2014. A emissão total foi estimada em 1.967 Mt CH_4, correspondendo a 55.080 Mt CO_{2eq} pelo GWP -AR5, e o carbono armazenado em 3.724 Mt, correspondendo a 13.655 Mt CO_{2eq}. As emissões de CH_4 aumentaram além da taxa de crescimento populacional devido ao aumento no consumo de papel per capita no país, de 0,02 kg de CH_4.ano^{-1} em 1961 para 0,30 kg de CH_4.ano^{-1} em 2016. A PNRS ainda não foi implementada e os cenários descritos indicam que, do ponto de vista das emissões de CH_4, seria mais vantajoso realizar a incineração em vez de aplicar outras tecnologias de tratamento de resíduos.

Palavras-chave: decomposição; mudança climática; papel higiênico; produtos florestais; resíduos.

1. Introduction

It is estimated that 11.2 billion tons of solid waste (SW) are collected and disposed of worldwide every day (UNEP, 2011; Leal Filho *et al.*, 2015). The decomposition of the organic fraction of this residue leads to greenhouse gas (GHG) emissions, contributing to climate change. GHG emissions worldwide reached the mark of 49 (± 4.5) Gt CO_{2eq}.year^{-1} in 2010, and the Waste sector participated with 1.5 Gt CO_2eq.year^{-1}, or 3% of that amount (IPCC, 2014a). GHG emissions released into the atmosphere need to be estimated and reported in the national GHG inventories by the parties under the United Nations Framework Convention on Climate Change (UNFCCC) (IPCC, 2000) and other agreements on global climate change.

SW is collected and disposed of in sites with higher or lower technological efficiency levels, implying distinct degrees of environmental impacts. In Brazil, it is estimated that, currently, 59% of the SW collected are disposed of in sanitary landfills (LF), the most advanced technology in the country for large-scale treatment. However, there is still a great number of municipalities that dispose of SW in inadequate sites, such as controlled dumps (CD) and open-air, uncontrolled dumps (UD) (ABRELPE, 2016). SW disposed under anaerobic conditions generates CH_4, a powerful GHG. The potential emission of this GHG may increase when control conditions are more advanced, such as in LF, when compared to CD and UD. In addition, technology is more efficient as CH_4 can be piped, recovered, and used for energy generation. SW incineration is not often used in Brazil and also generates GHG emissions, mainly carbon dioxide (CO_2) (MCTI, 2016), but not CH_4 (IPCC, 2000).

Despite the relatively small share of the Waste sector in total GHG emissions of the country, in 2010, it accounted for 14.8% of the total Brazilian CH4 emissions. SW disposal specifically accounted for 53.9% of the total CH_4 emissions, totaling 2,272 Mt, which corresponds to about 8% of the emissions of this GHG in the country. From 2005 to 2010, emissions from waste treatment in Brazil increased by 19.4%, being 7.3% in SW (MCTI, 2016).

Harvested Wood Products (HWP) are considered potential carbon sinks (IPCC, 2006). They play an important role in climate mitigation (Dias *et al.*, 2012; Donlan *et al.*, 2013; Kayo *et al.*, 2015; Yang & Zang, 2016), whose C emissions from sources or removals by sinks should be included in national GHG inventories after second commitment period of the Kyoto Protocol (IPCC, 2014b). Although C storage in HWP represents a sink, it can also become a source of GHG emissions as they are decomposed.

The accumulation of C from HWP in landfills received a different approach in the Intergovernmental Panel on Climate Change (IPCC) Guidelines 2006 (2006 GL) concerning the 2003 Good Practice Guidance (GPG) (IPCC, 2003; 2006). The HWP chapter of GPG considers the accumulation of C from HWP used and disposed of in a landfill, both as temporary (decomposing) and as permanent (non-decomposing) stocks. On the other hand, in the 2006 GL, the C accumulation from used HWP disposed in landfills has been considered in the Waste sector and only includes permanent C stocks.

Brazil is a major producer of pulp and paper. Domestic consumption is also growing, and so are the exports and imports (FAO, 2017). Among the types of paper that had a high increase in consumption in the past years are the sanitary and domestic use paper (SDUP), also called household paper, which includes toilet paper, napkins, paper towels for the kitchen, and other similar goods. This happened not only because of the population increase in Brazil but also because of higher per capita consumption. Recycling of these papers is minimal in the country, and their first disposal is essentially done in waste bins and then subsequently transported to LF, where available, or in many cases to CD and UD, which do not have adequate technology to control CH_4 emissions. Due to the wastewater treatment system adopted in the country, the sanitary and domestic papers already used by the consumer are not disposed of and treated together with sewage. CH_4 generated at solid waste disposal sites (SWDS) is released into the atmosphere, contributing severely to climate change, as its global warming potential is 28 times higher than that of CO_2 (UNEP, 2011).

Paper and paperboard account for about 15% of the SW gravimetric composition in Brazil (Corsten *et al.*, 2012), and used SDUP is entirely considered waste, unlike other papers suitable for recycling. Therefore, this residue will inevitably need to be treated in the systems previously mentioned (LF, CD, or UD). It is still unclear how the National Solid Waste Policy (NSWP), promulgated in 2010 (Brazil, 2010), could influence the disposal and treatment of this waste, mainly because technological changes in the systems are very sensitive to political and socio-environmental aspects, as is the case of incineration, for instance. The share of CH_4 emissions coming from the consumption of SDUP in Brazil is also unknown, as well as the technological alternatives to reduce them.

The objective of this study was to quantify CH_4 emissions coming from the disposal and treatment of sanitary and household papers in Brazil from 1901 to 2016 and to evaluate the storage of C that remains in the un decomposed waste in disposal sites (LF, CD, and UD), as well as to outline future scenarios to reduce emissions of this gas in the context of the NSWP.

2. Material and methods

2.1. Calculation procedure

2.1.1. Apparent consumption of SDUP

The apparent consumption of SDUP in Brazil in a given year i was calculated by the difference between the sum of production and imports minus exports:

(1)

$$AC(i) = P(i) + I(i) - E(i)$$

where:

$AC(i)$ = apparent consumption of SDUP in year i [t];

$P(i)$ = production of SDUP in year i [t];

$E(i)$ = exports of SDUP in year i [t];

$I(i)$ = imports of SDUP in year i [t];

i = index of the CH4 inventory year.

2.1.2. Mass of SW generated by SDUP in each SWDS

The masses of SW disposed of in each SWDS (LF, CD, and UD) every year i were calculated as follows (equations 2 to 4):

(2)

$$W_{LF}(i) = AC(i)\,.\ [\%LF(i)/100]$$

(3)

$$W_{CD}(i) = AC(i)\,.\ [\%CD(i)/100]$$

(4)

$$W_{UD}(i) = AC(i)\,.\ [\%UD(i)/100]$$

where:

$W_{LF}(i)$ = mass of SW disposed in LF in year i [t];

$W_{CD}(i)$ = mass of SW disposed in CD in year i [t];

$W_{UD}(i)$ = mass of SW disposed in UD in year i [t];

$\%LF$ = percentage of SW disposed in LF in year i;

$\%CD$ = percentage of SW disposed in CD in year i;

$\%UD$ = percentage of SW disposed in UD in year i.

2.1.3. CH_4 emissions

The CH_4 emissions by the SDUP waste disposed of in year i and in SWDS j were calculated by equations 5 to 10, following the specifications of the IPCC 2006 GL (IPCC, 2006; IPCC, 2014b):

(5)

$$CH_4emission(i,j) = CH_4generated(i,j) - R(i,j)\,.\ [1 - OX(i,j)]$$

where:

$CH_4emission(i,j)$ = CH_4 emitted from SDUP disposal in year i in SWDS j[tCH_4];

$CH_4generated(i,j)$ = CH_4 generated by SDUP disposal from organic matter decomposed in year i in SWDS j[tCH_4];

$R(i,j)$ = CH_4 recovered by SDUP disposal in year i in SWDS j[tCH_4];

$OX(i,j)$ = oxidation factor for year i depending on the waste management (fraction) in each SWDS j.

(6)

$$CH_4generated(i,j) = DDOCm_{decomp}(i,j)\,.\ \mathrm{F}\,.\left(\frac{16}{12}\right)$$

being:

$DDOCm_{decomp}(i,j)$ = decomposable degradable organic carbon of SDUP disposed of in year i in each SWDS j[t];

F = fraction of the generated methane at SWDS, in volume [fraction];

16 = atomic mass of CH_4;

12 = atomic mass of C.

(7)

$$DDOCm_{decomp}(i,j) = DDOCma(i-1,j)\,.\ (1 - \mathrm{e}^{-k})$$

being:

$DDOCma(i\text{-}1,j)$ = $DDOC$ accumulated at the end of year (i-1) at SWDS j[t];

k = reaction constant (year^{-1});

being:

(8)

$$k = \ln(2)/HL$$

and:

HL = half-life (years).

(9)

$$DDOCma(i,j) = DDOCmd(i,j) + \left[DDOCma(i-1,j)\,.\,\mathrm{e}^{-k}\right]$$

where:

$DDOCmd(i,j)$ = $DDOC$ deposited in year i at SWDS j(t).

(10)

$$DDOCmd(i,j) = W(i,j) \, . \, DOC(i,j) \, . \, DOCf(i,j) \, . \, MCF(i,j)$$

where:

W (i,j) = mass of degradable waste in year *i* in each SWDS *j* [t.ano^{-1}];

DOC (i,j) = organic degradable C in year *i*, fraction of C in waste in SWDS *j* [tC.t^{-1}];

DOCf (i,j) = fraction of C that may decompose in year *i* in SWDS *j* [fraction];

MCF (i,j) = methane correction factor to anaerobic conditions in year *i* in SWDS *j*[fraction].

2.1.4. Long-term durable C stored in SWDS

The amount of organic C that remains stored for the long-term (in durable condition) in SWDS was calculated by equation 11:

(11)

$$DOCm_{long-term}(i,j) = W(i,j) \, . \, DOC(i,j)\left[1 - DOCf(i,j)\right] . MCF(i,j)$$

where:

$DOCm_{long-term}(i,j)$ = organic C not decomposable that remains stored for a long-term in year *i* in SWDS *j*[tC].

2.2. Scenarios

Nine GHG emissions (CO_{2eq}) scenarios of SDUP waste were analyzed in this study, considering the implications of the NSWP promulgated in 2010 (Table 1). This law foresees the complete elimination of SWDS considered environmentally inadequate in the country after 2014, though it has not been enforced so far.

Equation 12 was applied to calculate the amount of electric energy potentially generated from the combustion of the CH_4 contained in the biogas recovered in the LF each year, as follows:

(12)

$$Energy_{LF}(i) = R(i) \, . \left[\frac{\left(\frac{CP_{CH4}}{D}\right)}{CONV}\right]$$

being:

$Energy_{LF}(i)$ = electric energy potentially generated from combustion of CH4contained in the biogas recovered from the LF in every year *i* [MWh];

R(i) = mass of CH4from biogas recovered in year *i* [t];

CP_{CH4} = average calorific power of CH_4 [MJ.Nm^{-3}];

D = CH_4 density [kg.m^{-3}];

CONV = energy-work equivalence converter [MJ.kWh^{-1}].

The GHG mitigation regarding energy use from the CH4 recovered in each year (2014, 2015, and 2016) was then calculated by multiplying the energy generated by the NIS emission factor (equation 13) because the electric energy produced from CH_4 combustion would be used to replace the electric energy supplied by the grid:

(13)

$$Emission_{LF-E}(i) = Energy_{LF}(i) \, . \, EF_{grid}(i)$$

where:

$Emission_{LF-E}(i)$ = CO_{2eq} emission from the energy generated from the combustion of CH_4 recovered in every year *i*, considering the emission factor of the Brazilian electric grid [tCO_2eq.year^{-1}];

$EF_{grid}(i)$ = emission factor of the Brazilian electric grid (NIS) [tCO_2eq. MWh^{-1}].

The mitigation related to the use of energy from CH_4 recovery in each year (2014, 2015, and 2016) was also calculated by multiplying the energy generated by the natural gas emission factor, which is the most commonly used fuel in Brazil as a backup to generate electricity in times of scarcity (equation 14). This means that CH_4 would be used as a fuel replacing natural gas, avoiding CO_2 emissions from this fossil fuel:

(14)

$$Emission_{LF-G}(i) = Energy_{LF}(i) \,.\, EF_{gas}$$

where:

$Emission_{LF-G}(i)$ = CO_{2eq} emission from the energy generated from the combustion of CH_4 recovered in every year i, considering the emission factor of natural gas [$tCO_2eq.year^{-1}$];

EF_{gas} = emission factor of natural gas [$tCO_2eq.MWh^{-1}$].

For the calculation of the amount of electric energy generated from SW incineration from discarded SDUP, we used equation 15, as follows:

(15)

$$Energy_I(i) = W(i) \,.\, CP_{SDUP} \,.\, \frac{1}{CONV} \,.\, \varepsilon$$

where:

$Energy_{LF}(i)$ = electric energy potentially generated from SDUP combustion in each year i [kWh];

$W(i)$ = mass of SW coming from SDUP used in year i [t];

CP_{SDUP} = average calorific power of SW from SDUP used in year i[$kJ.kg^{-1}$];

$CONV$ = energy-work equivalence converter [$MJ.\ kWh^{-1}$];

ε = combustion efficiency for electricity production [dimensionless].

The GHG mitigation of the use of energy from incineration in each year by applying the NIS emission factor was calculated by equation 16, as follows:

TABLE 1 – GHG emission scenarios by SW from SDUP used in Brazil after the promulgation of the NSWP in 2010

Scenario	Description
Current	Current situation of SW disposal from SDUP used in Brazil.
Current-E	Current situation of SW disposal from SDUP used in Brazil, taking into account that the CH_4 recovered in LF and combusted, would avoid the consumption of electricity produced in the Brazilian electric grid. It considers the average CO_{2eq} emission factor of the National Interconnected System (NIS).
Current-G	Current situation of SW disposal from SDUP used in Brazil, taking into account that the CH_4 recovered in LF, would avoid the use of natural gas, a fuel widely used in Brazil as a backup to generate electricity in times of scarcity.
PLF	It considers that the NSWP would be implemented at 100% from 2014 (as it should have been) and that all SW from SDUP used in Brazil would be only disposed of at LF.
PLF-E	It considers that the NSWP would be implemented at 100% from 2014 (as it should have been) and that all the SW from SDUP used in Brazil would be only disposed of at LF but takes into account that the recovered CH_4that would avoid the consumption of electricity produced in the Brazilian electric grid, considering the average CO_{2eq} emission factor of the NIS.
PLF-G	It considers that the NSWP would be implemented at 100% from 2014 (as it should have been) and that all the SW from SDUP used in Brazil would be only disposed of at LF but takes into account that the recovered CH_4 would be used to generate electricity and that CO_{2eq} emissions that would avoid the consumption of electricity produced in the Brazilian electric grid, considering the average CO_{2eq} emission factor of natural gas.
I	It considers that from 2014 all treatment of SW from SDUP used in Brazil would be done exclusively by incineration.
I-E	It considers that from 2014 all treatment of SW from SDUP used in Brazil would be done exclusively by incineration. It also takes into account that the energy generated by the incineration of SW would avoid the consumption of electricity produced in the Brazilian electric grid, considering the average CO_{2eq} emission factor of the NIS.
I-G	It considers that from 2014 all treatment of SW from SDUP used in Brazil would be done exclusively by incineration. It also takes into account that the energy generated by the incineration of SW would avoid the consumption of electricity produced in the Brazilian electric grid, considering the average CO_{2eq} emission factor of natural gas.

(16)

$$Emission_{I-E}(i) = Energy_I(i) \, . \, EF_{grid}(i)$$

where:

Emission$_I$ (i) = CO_{2eq} emission from the energy generated from SDUP incineration in year *i* [$tCO_2eq.year^{-1}$];

EF$_{grid}$ (i) = emission factor of the Brazilian electric grid (NIS) [$tCO_2eq.MWh^{-1}$].

Alternatively, the GHG mitigation related to the use of energy from SDUP incineration by applying the emission factor of natural gas was calculated by equation 17:

(17)

$$Emission_{I-G}(i) = Energy_I(i) \, . \, EF_{gas}$$

where:

Emission $_{LF-G}$ (i) = CO_{2eq} emission from the energy generated from SDUP incineration in every year *i*, considering the emission factor of natural gas [$tCO_2eq.year^{-1}$];

EF$_{gas}$ = emission factor of natural gas, corresponding to the mass of CO_2eq per MWh produced from natural gas combustion [$tCO_2eq.MWh^{-1}$].

2.3. Data utilized

SDUP production, import, and export data were obtained directly from the FAOSTAT system (FAO, 2017). Methane recovery data in LF for the 2003 to 2010 period were obtained from the Waste Sector Reference Report, part of the Third National Communication of Brazil to UNFCCC (MCTI, 2015). Methane recovery was assumed to be null

TABLE 2 – Activity data and emission factors from SDUP treated in distinct SWDS used to calculate CH4 emissions in Brazil.

Variable			Value	Unit	Source
F	Fraction of the generated methane at SWDS, in volume		0.4	dimensionless	MCTI (2015)
OX	Landfill *(OX (i, LF))*		0.1	dimensionless	IPCC (2006)
	Controlled dump *(OX (i, CD))*		0.0	dimensionless	IPCC (2006)
	Uncontrolled dump *(OX (i, UD))*		0.0	dimensionless	IPCC (2006)
k			0.07	$year^{-1}$	IPCC (2006)
DOC			0.44	$tC.t^{-1}$	IPCC (2006)
DOCf			0.5	dimensionless	IPCC (2006)
MCF	Landfill *(MCF (i, LF))*		1	dimensionless	MCTI (2015)
	Controlled dump *(MCF (i, CD))*		0.8	dimensionless	MCTI (2015)
	Uncontrolled dump *(MCF (i, UD))*		0.4	dimensionless	MCTI (2015)
EFgrid		2014	0.1355	$tCO_2eq.MWh^{-1}$	MCTI (2016)
		2015	0.1244		MCTI (2016)
		2016	0.0817		MCTI (2016)
CP_{CH4}(average CH_4 calorific power)			35.9	$MJ.Nm^{-3}$	Rosa *et al.* (2016)
D (CH_4 density)			0.7154	$g.m^{-3}$	IPCC (1996)
Mean calorific power of tissue paper			15.200	$kJ.g^{-1}$ (dry basis)	Gavrilescu (2008)
CONV (Energy-work equivalence)			3.6	$MJ.kWh^{-1}$	Bernardi (2009)
Average efficiency of CH_4 recovery in LF in Brazil			0.2438	dimension less	MCTI (2015)
Average efficiency of SW incineration			0.2500	dimensionless	Demertzi *et al.* (2015)

before 2003. A projection of methane recovery for the 2011-2016 period was also made based on the available data, assuming a linear trend curve, which fitted well with actual data.

The variables used in the calculations, values adopted in this work, units, and sources are listed in Table 2. It was preferred to use national references, when available, and the 2006 GL. The percentages of solid waste treatment in each category of SWDS (LF%, CD%, and UD%) employed here were obtained from actual data published in 1989, 1995, 2000, 2003, 2008, 2014, 2015, and 2016 (IBGE, 2000, 2008; ABRELPE, 2016) with the other years being linearly interpolated (Figure 1).

3. Results

3.1. Methane emissions

The SDUP production in Brazil increased from 47,900 t in 1961 to 1,146 Mt in 2016 (FAO, 2017), resulting in a cumulative total of 23,723 Mt. Imports and exports totaled 188,147 t and 498,786 t in the period, respectively, which resulted in apparent consumption of 24,259 Mt accumulated between 1961 and 2016. Variation in the apparent consumption in the period was noticed, from 48,200 t in 1961 to 1,146 Mt in 2016. The country´s population showed growth from 17 M in 1901 to 71 M in 1961 and 205 M in 2016, implying a significant increase in the apparent per capita SDUP consumption in the country, from 0.68 $kg.year^{-1}$ in 1961 to 5.52 $kg.year^{-1}$ in 2016.

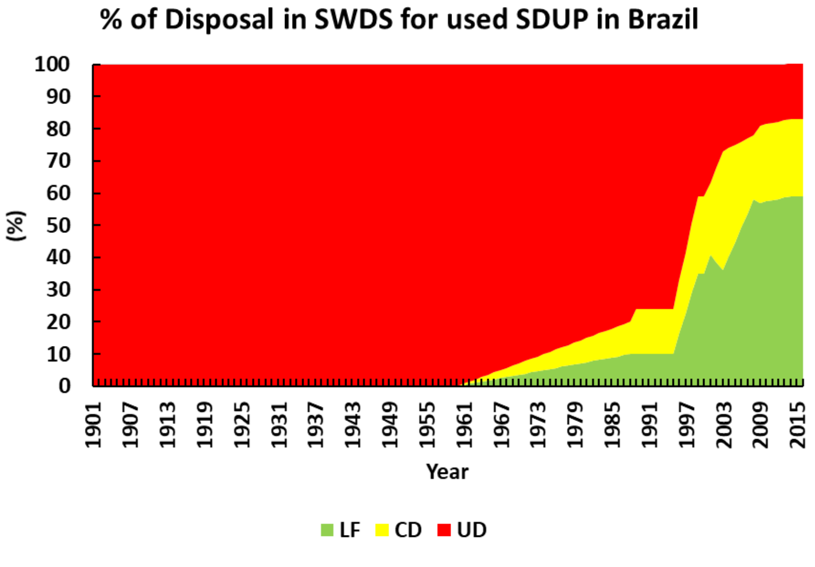

FIGURE 1 – Share of SW from used SDUP in Brazil.

LEGEND: Actual data in 1989, 1995, 2000, 2003, 2008, 2014, 2015 and 2016; other years data were obtained by linear interpolation. LF: landfill, CD: controlled dump, UD: uncontrolled dump.

A technological evolution regarding SW disposal in Brazil has been reported, with the growing adoption of LF as the reference treatment. This technology was very incipient by the mid-1990s when CD and UD were the SWDS widely used throughout the country. However, measures were adopted to improve SW treatment, resulting in a remarkable evolution. In 2016, 59% of the collected residues were disposed of in LF, 24 % in CD, and 17% in UD. Despite this remarkable progress, the last decade is characterized by stagnation of this evolution process (Figure 1).

Assuming all SDUP consumed in Brazil after use is disposed of in one of the three types of SWDS and that the generation of residues follows the population growth curve over time, it is estimated that 23,723 Mt of waste resulting from used SDUP has been produced in Brazil during 1901-2016. In the period 1901 to 2016, 8.811 Mt of SW were treated in LF (36.2%), 4.846 Mt in CD (20.0%), and 10.602 Mt in UD (43.70%), with 1997 being the year of the highest amount of SW disposed of in dumps, sites considered environmentally inadequate (Figure 2). Therefore, it can be deduced that there has been an improvement in the disposal of SDUP waste in Brazil, but more substantial advances are still needed.

Deposited organic C (*DDOCmd*) from SDUP used and disposed of totaled 3,724 MtC in the analysis period, being 1,938 MtC in LF, 852,000 tC in CD, and 933,000 tC in UD. This corresponds to 13.65 $MtCO_{2eq}$, considering the three SDWS. The corresponding values of accumulated organic C (*DDOCmd*) in 2016 were 12,170 MtC, 6,331 MtC and 10,187MtC in LF, CD, and UD (total 28,688

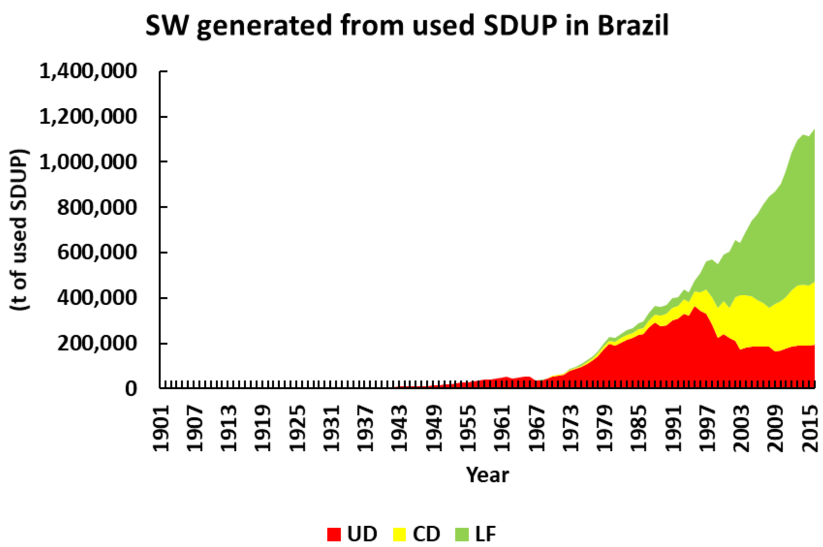

FIGURE 2 – Mass (t) of SW generated by SDUP use in Brazil and disposed at different SWDS.
LEGEND: LF: landfill, CD: controlled dump, UD: uncontrolled dump.

MtC or 105,188 $MtCO_{2eq}$). Extending the analysis to 2061, they increased to 27,966 MtC, 12,346 Mt C, and 13,644 Mt C (sum gives 53,958 Mt C, corresponding to 197,844 Mt CO_{2eq}), respectively in LF, CD, and UD. The values of decomposed organic C ($DDOCm_{decomp}$) were estimated in 2016 at 742 MtC, 397 ktC, and 671 ktC in LF, CD, and UD (total 1,810 MtC or 6,636 $MtCO_{2eq}$), and up to 2061 to 1,887 MtC, 833 thousand tC and 922 tC (totaling 3,642 MtC or 13,354 $MtCO_{2eq}$), respectively in LF, CD, and UD.

The organic C remaining in SWDS for a long-term period ($DDOCm_{long\text{-}term}$), which is originated from SDUP use and disposal, was quantified at

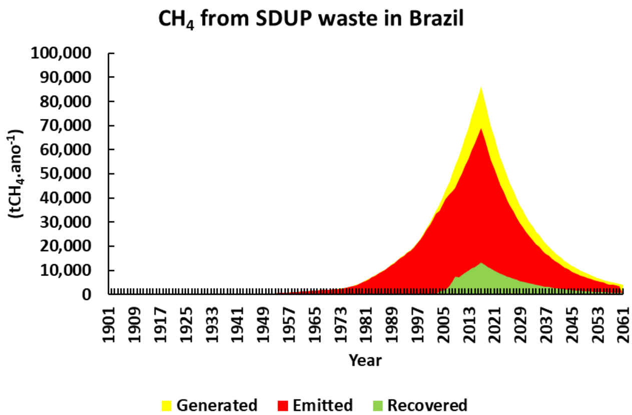

FIGURE 3 – CH_4 generated, recovered and emitted from SDUP waste in Brazil in different SWDS.

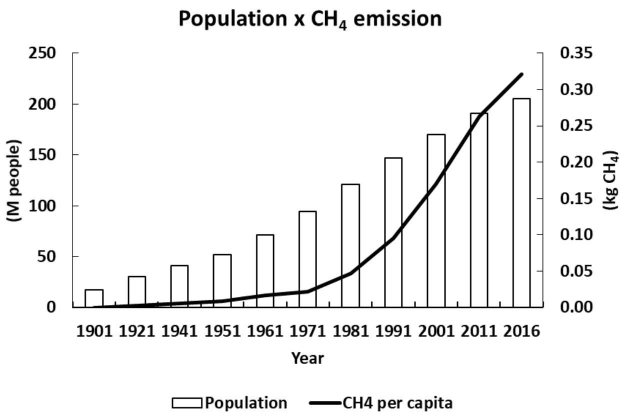

FIGURE 4 – Population and per capita CH_4 emissions from SW generated by SDUP disposal in Brazil during 1901-2016.

1,938 Mt C, 426 kt C, and 933 kt C, respectively in LF, CD, and UD, totaling 3,298 Mt C, which corresponds to 12,092 Mt CO_{2eq}, considering the entire period of analysis, i.e. 1901-2016.

The CH_4 generation by 2016 was estimated at 495,000 tin LF, 265,000 tin CD, and 447,000 tin UD, totaling 1,207 Mt CH4, which corresponds to 33,787 $MtCO_{2eq}$. By 2061, these values would increase to 1,258,000 t, 555,000 t, and 614,000 t, respectively, reaching 2,428 $MtCH_4$, a value which corresponds to 67.990 $MtCO_{2eq}$. It was estimated that 163,000 tCH_4 were recovered in LF by 2016 and 461,000 tCH_4 by 2061, corresponding to 4,570 $MtCO_{2eq}$ and 12,909 $MtCO_{2eq}$. The emission was estimated to be 331,000 tCH_4 by 2016 and 797,000 tCH_4 by 2061 in LF, 265,000 tCH_4 by 2016, and 555,000 tCH_4 by 2061 in CD, and 447,000 tCH_4 by 2016, and 614,000 tCH_4 by 2061 in UD. In total, 1,043 $MtCH_4$were emitted by 2016, and 1,967 $MtCH_4$ would be emitted by 2061, corresponding to 29,218 $MtCO_{2eq}$ and 55,080 $MtCO_{2eq}$, respectively (Figure 3).

The per capita consumption of SDUP increased in the country during the last century leading to growing individual CH4 emissions, from 0.02 $kg.year^{-1}$ in 1901 to 0.30 $kg.year^{-1}$ in 2016 (Figure 4). These values correspond to 0.43 and 8.48 kgCO2eq. $year^{-1}$ per person. Therefore, on average, Brazilians are consuming more SDUP and emitting more CH_4, despite the technological evolution that happened in the period regarding waste collection and treatment.

3.2. Long-term stocked carbon

From 1901 to 2016, 3,724 Mt C were stored in SWDS, being 1,938 Mt C in LF, 852 k t C in CD, and 933 k t C in UD. This corresponds to 13.65 Mt CO_{2eq}, considering all the SWDS examined. C storage up to 1994 was mostly due to waste disposal in UD, but it changed afterward with the technological

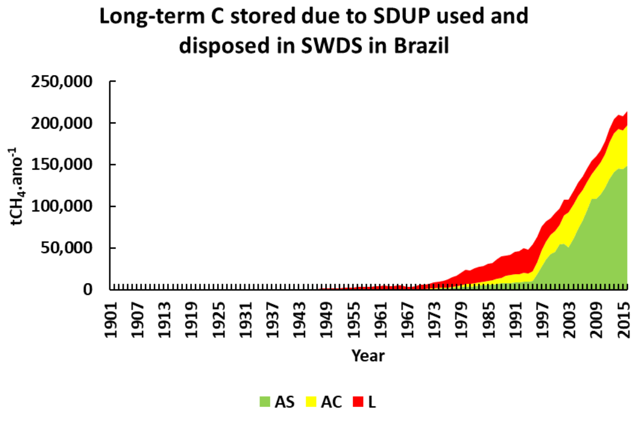

FIGURE 5 – Long-term C stored originated from SDUP and disposed in SWDS.
LEGEND: LF: land fill, CD: controlled dump, UD: uncontrolled dump.

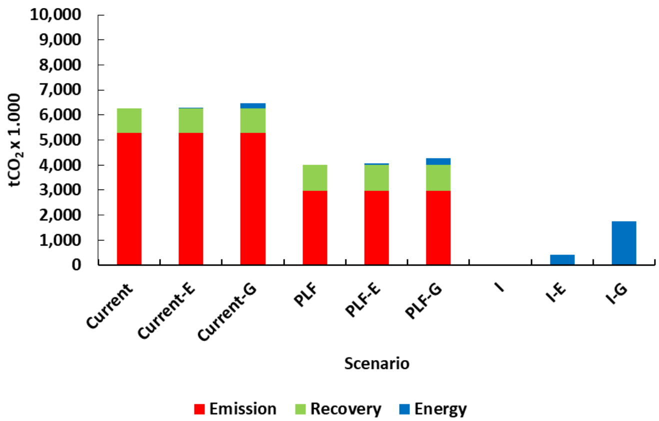

FIGURE 6 – CO_{2eq} emission scenarios from used SDUP disposal in SWDS in Brazil during 2014-2016, considering the Brazilian NSWP Law. Scenarios as described in Table 1.

improvement of SW treatment in the country. Due to the anaerobic conditions in LF, there was greater storage of C in this SWDS from the mid-1990s. In 2016, the long-term C storage was 69% in LF, 23% in CD, and 8% in UD (Figure 5). The accumulated C storage throughout the 1901-2016 period was as follows: 52% in LF, 23% in CD, and 25% in UD.

3.3. Scenarios after the promulgation of the NSWP

The NSWP promulgated in 2010 established as mandatory the appropriate treatment of SW throughout the country from 2014. However, its goals were not accomplished due to several economic and political reasons. Currently, more than 40% of SW is still disposed of in dumps, which are considered environmentally inadequate. If that law were to be implemented and all the SW originated from used SDUP were disposed of and treated in LF, there would be a reduction of 67% in CH_4 emissions (39,530 tCH4.year-1equivalent to 1,107M $tCO2_{eq}$.year^{-1}) within the period 2014-2016, only by biogas recovery and destruction (PLF scenario compared to the Current scenario). If the NSWP were put in practice, but with the adoption of incineration instead of LF treatment, there would be a 100% reduction of CH_4 emissions because this SW treatment technology does not cause CH4 emissions (scenario I) (Figure 6).

In the current scenario, without the implementation of the NSWP, but considering that there would be electricity generation from biogas (CH_4) from 2014 to 2016, and by applying the emission factor of the Brazilian electric grid, there would be a small emission reduction, of 1,047 tCH_4.year^{-1}, which is equivalent to 29,310 $tCO_{2eq.}$ year^{-1} (Current-E scenario compared to the Current scenario). Considering the scenario without implementation of the NWSP and generation of electricity and applying the natural gas emission factor, 4,528 tCH_4.year^{-1} would be no longer emitted, which corresponds to 126,787

$tCO_{2eq.}$ $year^{-1}$ (Current-G scenario compared to the Current scenario).

The scenario of implementation of the NSWP combined with electric power generation, by applying the emission factor of the grid, would lead to an emission reduction of 40,597 t CH_4.$year^{-1}$, corresponding to 1,137M t CO2eq.year-1 (PAS-E scenario compared to the Current scenario). On the other hand, the implementation of the NSWP combined with electricity generation from biogas combustion from 2014 to 2016, and applying the natural gas emission factor, would result in emission saving of 44,154 t CH_4.$year^{-1}$, which corresponds to 1,236 Mt $CO_{2eq.}$$year^{-1}$ (PAS-G scenario).

Considering the incineration scenario, the corresponding emission avoidance (mitigation) would be 63,763kt CH_4.$year^{-1}$, that is, 1,785 Mt $CO_{2eq.}$$year^{-1}$ (scenario I-E compared to the Current scenario), if the NIS were applied. For the analogous scenario, applying the emission factor of natural gas, 79,688 tCH_4.$year^{-1}$ would be left to emit into the atmosphere, i.e.2,231 $MtCO_{2eq}$.$year^{-1}$ (scenario I-G).

4. Discussion

In line with the world's growth, Brazil has significantly increased its population since 1901. With more than 200 M in habitants, this country is today the third-largest SW generator in the world, after the United States and China. Despite this fact, urban SW generation per capita (1.03 $kg.day^{-1}$) is still at intermediate levels, far below most developed countries but close to China´s figure (1.02) (World Bank, 2012).

By itself, the population increase has led to higher consumption of SDUP in Brazil, but the fact to highlight is that per capita consumption exceeded population growth, which denotes the intensification of the use of this product by Brazilians in the last decades. On the other hand, the higher SDUP consumption implies a greater generation of SW, where SDUP is an important part because, in Brazil, this residue is not discarded in the toilet, being placed in toilet containers. Practically 100% of the SDUP disposed of in the country inevitably stops in LF, CD, or UD. There are no country's official data regarding the share of SDUP in SW gravimetry, but some studies suggest 6.40 to 6.70% (Casaril *et al.*, 2009), 8.00% (Coentro & Demamboro, 2017) and 12.46% (Galdino & Martins, 2016). From the data used in this study, we estimated that the percentage of these residues throughout the SW in the country is 1.46% on a dry basis (as in 2016). Assuming that all SDUP is disposed of in LF, CD, and UD, the per capita generation of this waste is 5.58 $kg.year^{-1}$, which is equivalent to the annual consumption per person of this kind of paper. Thus, the per capita CH_4 emission regarding SDUP consumption in 2016 was estimated at 0.30 $kgCH_4$.$year^{-1}$, corresponding to 8.48 $kgCO_{2eq.}$$year^{-1}$.

The growing waste generation from SDUP use and disposal has not been accompanied by the compatible technological improvements for its treatment in Brazil in the last decade. We noticed stagnation in the percentage of participation of LF in treatment, and no significant progress in using more efficient and sustainable technologies has been evidenced. As previously mentioned, SDUP is non-recyclable waste, and in Brazil, it has as final destination LF, CD, or UD, except in a few very specific cases. Law No. 12.305, of August 2nd, 2010, instituted the National Solid Waste Policy (NSWP), which has as its first guideline (according to the National Solid Waste Plan) (MMA, 2012) the complete elimination of CD and UD in four years after the date of publication of the Law, i.e. 2014 (ABRELPE, 2016).

The most up-to-date data available shows that the NSWP Law did not achieve its purpose. The waste generation remains at high levels, recycling has not evolved, and reverse logistics have not been materialized. More than 3,000 municipalities have an inadequate destination for SW (ABRELPE, 2016). The NSWP targets were not reached in 2014, nor were effective several other actions planned to improve solid urban waste management. New deadlines for the effective implementation of this plan are under discussion, with staggered targets between 2018 and 2021 varying with the size of municipalities (Teodósio *et al.*, 2016).

Unfortunately, as previously stated, the NSWP was unable to reverse the paradigm of inadequate disposal of SW in Brazil, which results in higher emissions of CH4 to the atmosphere. This study clearly shows the effects of SDUP consumption and waste disposal on CH_4 emissions in the country. If the SW Law were to be seriously demanded and implemented in practice by the municipalities, there would not be an immediate reduction of CH_4 emissions because the SW disposed of in previous years would still produce emissions. However, the combination of better disposal and energy utilization of the biogas or the waste itself would make a major and immediate contribution to the mitigation of CH_4 emissions. The recovery of CH_4 in Brazil is not very expressive, mainly due to the low efficiency of LF (about 24%). The increase of this efficiency to more acceptable levels, around 60% (Silva *et al.*, 2013), would allow even higher gains.

In addition to CH_4 emissions, the disposal of used SDUP implies C accumulation at disposal sites since part of the organic matter does not decompose or decompose very slowly (IPCC, 2006). This storage of C in SWDS constitutes a sink but unfortunately also represents a large volume of immobilized waste, which occupies space and can have adverse environmental impacts. Therefore, despite this being an HWP that stocks C, its environmental benefits might be controversial.

The status quo (Current scenario) is effectively not encouraging, i.e. the current form of SW disposal from used SDUP generates CH_4 emissions that could be avoided and converted into renewable energy as well. LF has been reported as an adequate SW treatment for Brazil, but parallel discussions about the possible use of other technologies, such as incineration for example (Brazil, 2010; Assamoi & Lawryshyn, 2012; Dong *et al.*, 2013; Leite, 2016), have also been done. In Brazil, this option is laden with controversy due to the potential health damage that can be caused by the emission of substances harmful to human health and the environment. However, some studies show that this point of view predominates on the historical use of obsolete equipment. Some papers point out that more efficient systems for gas emissions control already exist in the market and, together with more rigid legislation, indicate incineration as environmentally safe and economically feasible for SW treatment in the country (Martins, 2017). It was demonstrated in this work that incineration can eliminate CH_4 emissions from SDUP waste and, combined with energy utilization, is the option that brings the greatest contribution in terms of climate change mitigation. Wang *et al.* (2012) assessed the environmental profile and greenhouse gas emissions for three different paper waste destinations: bioethanol production, recycling, and incineration with energy recovery. Several scenarios, including different technologies and paper types, were considered indicating that, in general, incineration, when using high-level technology, becomes the preferable option to manage paper waste.

5. Conclusions

Most of the SDUP produced in Brazil is consumed internally, generating 1 Mt of SW disposed of annually (2016 basis), which corresponds to about 1.5% of all SW generated in the country. This waste is disposed of in different SWDS, and currently, about 60% is laid out in LF. Although an evolution in the SW treatment in Brazil during the last century has been noticed, the last decade has been characterized by little progress.

The total CH_4 emission during 1901-2016 was 1,967 Mt, which corresponds to 55,080 Mt CO_{2eq} by GWP-AR5, and the long-term stocked C was estimated at 3,724 Mt C, corresponding to 104,282 Mt CO_{2eq}. CH_4 emission increased beyond the population growth rate, due to the growing per capita paper consumption, from 0.02 kg CH_4.year^{-1} in 1961 to 0.30 kg CH_4.year^{-1} in 2016.

The National Solid Waste Policy (Law no. 12,305/2010, Art. 54) determined the complete elimination of environmentally unsuitable SWDS by 2014, which did not comply yet. The scenarios outlined in this study indicated that, from the perspective of CH_4 emissions, to meet the goal of the National Solid Waste Plan, it would be more advantageous to incinerate the SW from the SDUP instead of treating it in LF, once incineration avoids CH_4 emissions and generate renewable energy as well. However, other aspects related to the emission of substances potentially hazardous to human health, particularly persistent organic pollutants, must be taken into account.

Acknowledgements

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001. CRS thanks to the fellowship granted by CAPES – Ministry of Science, Technology, and Communications, Brazilian Federal Government. ACD acknowledges the financial support to CESAM (UID/AMB/50017/2019) through national funds and the co-funding by FEDER within the PT2020 Partnership Agreement and Compete for 2020.

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