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Analysis of potential for reducing emissions of greenhouse gases in municipal solid waste in Brazil, in the state and city of Rio de Janeiro

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ABSTRACT

This paper examines potential changes in solid waste policies for the reduction in GHG for the country of Brazil and one of its major states and cities, Rio de Janeiro, from 2005 to 2030. To examine these policy options, trends in solid waste quantities and associated GHG emissions are derived. Three alternative policy scenarios are evaluated in terms of effectiveness, technology, and economics and conclusions posited regarding optimal strategies for Brazil to implement. These scenarios are been building on the guidelines for national inventories of GHG emissions (IPCC, 2006) and adapted to Brazilian states and municipalities' boundaries. Based on the results, it is possible to say that the potential revenue from products of solid waste management is more than sufficient to transform the current scenario in this country into one of financial and environmental gains, where the negative impacts of climate change have created a huge opportunity to expand infrastructure for waste management.

1. Introduction

Brazil, the largest country in South America (47% of continent's territory) and the world's fifth largest in land area, is a federation divided into five geographic regions (Midwest, Northeast, North, South, and Southeast), formed by 26 states plus a Federal District, divided into municipalities. The country has the largest economy[1] in Latin America, the second in the Americas (behind only the USA), the sixth in the world at market rates of exchange and the seventh in purchasing power parity, but its per capita gross domestic product (GDP) is 64th in the world (World Bank, 2011). However, Brazil is the tenth largest consumer of energy on the planet and the third in the Western Hemisphere, behind USA and Canada. Its electric energy mix is mostly based on renewable sources (88.8% of total production), mainly hydropower, which accounts for the generation of 467 TW h (81.7% of total production), with installed capacity of 570 TW h. The world average is 19.5% from renewable sources (MME, 2012).

Fig. 1 shows the location of Brazil in South America and the state and city of Rio de Janeiro in Brazil. A summary statistics about population, area, GDP, and climate are shown in Table 1 for Brazil, Rio de Janeiro state and city.

The state of Rio de Janeiro is located in the eastern portion of the country's Southeast region. It is slightly larger than Denmark. According to data from the 2010 Census (IBGE, 2011), Rio de Janeiro is the third most populous state in Brazil. A large part of the state's economy is based on the provision of services. There is also significant participation of industry but little influence of the agricultural sector. It has the second largest economy in Brazil, behind only the state of São Paulo, and the fourth in South America, with GDP higher than Chile and a 10.9% share of national GDP (CEPERJ, 2011; IBGE, 2012).

The city (municipality) of Rio de Janeiro, capital of the state, is the second largest city in Brazil, South America's third and 24th in the world in population (IBGE, 2011). It is the best known Brazilian city abroad. It has the country's second largest municipal GDP and 30th largest in the world, equivalent to 5.4% of the national total. The service sector accounts for the largest share of GDP (65.52%), followed by collection of taxes (23.38%), industrial activity (11.06%), and agriculture (0.04%).

The weather is a relevant factor for the treatment of waste in Brazil since it favors the anaerobic decomposition of waste in landfill cells.

1.1. Organization of the solid waste sector

Solid waste can be classified as municipal, industrial and from health services. Municipal solid waste (MSW) is formed of a mixture of household waste (residential and commercial waste), sweepings from streets, parks and gardens, and sludge. The indus-

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[1] Brazil's currency is the Real (BRL).

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Fig. 1. Location of Brazil in South America and of the state and city of Rio de Janeiro. *Source:* Guianet, 2012

Table 1
Population, area, GDP and climate of Brazil, RJ State and Rio de Janeiro City. *Sources:* CEPERJ (2011), IBGE (2011), IBGE (2012), World Bank (2011).

Geographic area	Population (inhabitants)	Area (km^2)	GDP per capita (USD)	Climate
Brazil	190,755,799	8,514,876	10,120	Tropical
RJ State	15,989,929	43,780	10,520	Tropical and altitude tropical
Rio de Janeiro City	6,320,446	1,200	13,520	Atlantic tropical

trial solid waste (ISW) involved in GHG emissions in this study is considered non-hazardous (Class II-A[2]) because this portion of industrial waste comprises organic debris and other degradable materials. The waste from health services (HSW) is only important for GHG emissions if incinerated, mainly due to the content of paper and plastic items.

In Brazil, the solid waste can generally be recycled, composted, incinerated, or landfilled, but deposit in open dumps is the most common practice. The amounts of CH_4, CO_2, and N_2O emitted vary

[2] According to ABNT NBR 10004:2004 (ABNT, 2004), Class II-A residues (non-inert) are those that do not fit the classifications of Class I waste (hazardous) or Class II-B waste (inert), and can have properties such as biodegradability, combustibility or water solubility.

Table 2
Current characterization of solid waste in Brazil, RJ State and Rio de Janeiro City. *Sources:* ABRELPE (2010), COMLURB (2010), Rovere et al. (2007), and Authors.

Features	Brazil	RJ State	Rio de Janeiro City
Solid waste daily production (tonnes)	161,000	15,000	9,000
Sanitary landfilling (by weight)	57%	14%	100%
Controlled landfilling (by weight)	24%	65%	0%
Open dumps and others	19%	21%	0%

Table 3
Increase in collection and disposal of ISW in Brazil in relation to previous year from 2004. *Source:* ABRELPE (2010).

Year	Total ISW collected (%)	ISW sent to class II-A landfill (%)	ISW incinerated (%)
2004–2005	+8.65	−7.37	+31.96
2005–2006	+39.23	+85.97	+1.03
2006–2007	+33.51	+22.44	+10.86

depending on the amount of garbage produced, the content of organic matter in its composition, and the anaerobic conditions of disposal.

A sanitary landfill acts as a large bioreactor, where biodegradation of organic matter in waste occurs in a predominantly anaerobic environment. This degradation results in the generation of biogas (or landfill gas – LFG), mainly composed of CO_2 and CH_4, which are greenhouse gases, the latter with global warming power 21 times larger than the former.

The CO_2 produced when burning waste from renewable sources does not impact the climate, since being of biogenic origin, because it is sequestered in the carbon cycle.

The N_2O is produced in circumstances where there is participation of waste, and its importance also depends on the type of treatment (composting) and the conditions.

This study aims to analyze the avoided emissions by climate change policies, plans, and government programs already running, in implementation phase and in possible future implementation.

Table 2 presents the daily generation of solid waste in the three geographical areas in study, as well as the destination of this waste that goes to landfills by treatment quality.

1.1.1. Characterization of solid waste sector in brazil

In Brazil, solid waste management is carried out by municipalities, either independently or through consortiums between neighboring and nearby municipalities. The main source of information regarding the quantity produced was the National Basic Sanitation Survey (IBGE, 2010), which brings together the results of research on the supply and quality of sanitation services in the country, based on a survey conducted among the municipal government entities and private contractors hired to provide water supply, sewerage, urban drainage, and garbage collection. There were 5,507 Brazilian municipalities at the time of the survey.

In this country, it is often difficult to distinguish between dump areas, landfills under supervision and sanitary landfills, and many nominally sanitary landfills in a strict classification would be categorized as dump areas (Mahler and Loureiro, 2009). The way that sanitary landfills are designed and constructed, and any small flaw in management or in operation can be sufficient to reclassify them as dump areas or supervised landfills. This can be noticed in sanitary landfills in big cities and in controlled landfills in big and medium size cities, which despite being well maintained present serious problems in boundary conditions that will be detected only by future generations. Moreover, in small cities where the local administration is not committed to preserving the environment for current and future generations, usually, a single bulldozer can turn a reasonably well managed landfill into a dump area in only one month. Unfortunately, the transformation of a dump area into a sanitary landfill is an almost impossible mission (Mahler et al., 2010).

As discussed above, part of industrial waste is included in this study, since it contributes to total GHG emission: the amount that goes to Class II-A landfills and incineration. According to ABRELPE (2010), in 2004, was collected 2,946.8 tonnes of ISW in Brazil, 58.8% of which went to landfills and 1.6% to incinerators. Table 3 presents the increase in ISW collected from 2004 to 2007.

For the waste from health services, the data were obtained from the second national inventory (MCT, 2010), which found the burning of 6568 tonnes in 2005, and ABRELPE (2010), citing 8374 tonnes incinerated in 2008.

1.1.2. Characterization of solid waste sector in the state of Rio de Janeiro

The solid waste management of the state of Rio de Janeiro, which is composed of 92 municipalities, in 2005 was 4 licensed landfills, 13 "controlled" landfills, and 6 landfills in the licensing stage; 4 sorting and composting[3] units in the implementation phase, 53 deployed sorting and composting facilities, with only 26 operating normally, and 62 dumps,[4] among which 48 have the presence of scavengers and their families, livestock, and disease vectors.

Among the landfills in operation, there is an expectation that the Adrianópolis Waste Treatment Center (CTR[5]), which produced 3,000 m^3/h of biogas in 2005, will in 2022 reach production of 14,000 m^3/h, with capacity to generate 10 MW of electricity, enough to light roads and public buildings in a city of one million people (Rovere et al., 2007). The calculation of per capita generation of household and industrial waste came from the historical data supplied by the Rio de Janeiro Municipal Urban Sanitation Company[6] (COMLURB, 2010) and the Inventory of Anthropogenic Emissions of Greenhouse Gases in the State of Rio de Janeiro 2005 (Rovere et al., 2007).

From these data and correlating with per capita GDP in the case of municipal waste, and industrial GDP in the case of industrial waste, we estimated the solid waste generation and gravimetric composition, adopting the function shown in Fig. 2. For the choice of functions, we used the concepts defined in the theories of the neoclassic economic growth model. This is an important parameter because higher per capita GDP will lead to higher consumption in general and, consequently, increased generation of waste and of greenhouse gases.

From the state inventory of GHG, we calculated the weighted average rate of per capita generation, 1.212 kg/person/day, so we adjusted the curve by projecting similar growth rate for the city and state.

[3] Composting is an aerobic process where a large fraction of degradable organic carbon (DOC) is converted to carbon dioxide (CO_2). CH_4 is formed in anaerobic parts of the compost, but is oxidized to a large extent in aerobic parts of the compost. The estimated CH_4 released into the atmosphere varies from less than 1% of the total initial carbon waste (IPCC, 2006).

[4] "Dump" is used to classify waste landfill sites with poor or without any form of control (Loureiro, 2005).

[5] The CTR is formed by a set of integrated technologies in different treatment units able to promote the complete management of various types of waste, such as landfill, leachate treatment, recycling, composting, inerts reuse units (such as waste construction) and tree pruning, arboretum, laboratories, environmental education center, power generation plants (with the use of biogas).

[6] COMLURB is owned by the Rio de Janeiro municipal government.

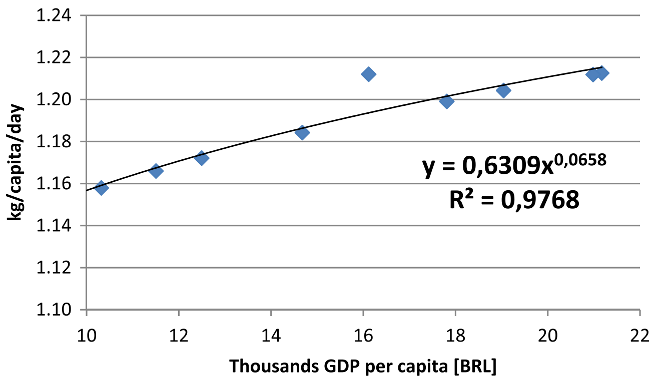

Fig. 2. Evolution of household waste generation in function of per capita GDP in RJ state.

Table 4
Evolution of household waste per capita and ISW generation in the state of RJ.

Year	Household waste (kg/capita/day)	Industrial waste (10^3 ton/year)
2005	1.212	816.5
2010	1.215	1123.9
2015	1.227	1475.8
2020	1.240	1974.9
2025	1.254	2642.9
2030	1.268	3536.8

Table 5
Behavior of organic material and paper in function HDI (%) in the State of RJ. *Source:* COMLURB (2009) and UNPD (2008).

Year	HDI	% OM	% Paper
2005	0.832	51.52	19.39
2010	0.868	50.44	20.58
2015	0.894	49.63	21.47
2020	0.922	48.80	22.40
2025	0.950	47.94	23.35
2030	0.979	47.05	24.32

With regard to industrial waste, data on its generation were estimated from the total output of industries in the state of Rio de Janeiro, according to data from Rovere et al. (2007). Most of this type of waste is produced in the metropolitan area of the state (covering the municipality of Rio and its suburban municipalities). The first-degree function considers the best scenario, since there would be no generation of industrial waste without industrial production. Table 4 below shows the evolution of all this waste generation.

The gravimetric composition of collected waste in the state of Rio de Janeiro in 2005 was 54% food, 1% garden cuttings, 17% paper, 2% wood, 2% textile and 24% plastic, metal, and other inert materials. These factors should be modified due to the increase in the state's human development index (HDI), particularly with respect to the content of organic matter (OM), which should decrease, thereby reducing methane emissions.

The percentage of gravimetric composition of the residues was estimated, year by year, for use in calculations of the carbon content of each waste component. Data from COMLURB (2009) were used to project trends in waste composition of the state, as shown in Table 5, due to the increase in the HDI up to 2030 (UNPD, 2008). We estimated the percentage of other degradable waste materials similarly.

Table 6
Household per capita and industrial waste deposited in Rio de Janeiro City Landfills – Historical Series. *Source:* COMLURB (2010).

Year	Household waste (kg/capita/day)	Industrial waste (10^3 tonne)
1996	0.719	11.8
1997	0.744	6.6
1998	0.765	17.2
1999	0.794	26.7
2000	0.824	15.8
2001	0.832	18.2
2002	0.852	27.2
2003	0.813	58.7
2004	0.805	76.0
2005	0.807	40.2
2006	0.830	51.3
2007	0.820	71.9
2008	0.844	71.8

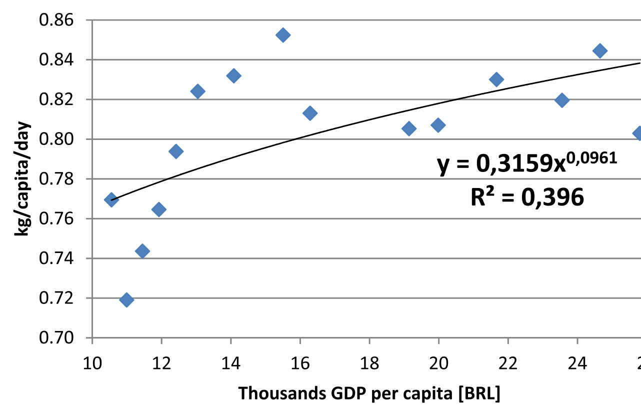

Fig. 3. Evolution of household waste generation as a function of per capita GDP in Rio de Janeiro city.

1.1.3. Characterization of solid waste sector in Rio de Janeiro city

According to COMLURB (2010), the total amount of waste landfilled in 2005 was household waste and large generators[7]: health service providers, public agencies, industries, and private parties,[8] including destroyed products.[9]

The collected waste of Rio de Janeiro is disposed in two controlled landfills: Gericinó (Bangu district of the city) and Gramacho (municipality of Duque de Caxias). Even though wastes are disposed of in surrounding municipalities, the responsibility for emissions rests upon the waste generator (IPCC, 2006).

The per capita household and industrial waste deposited in landfills, provided by the COMLURB series, are presented in Table 6 for the years 1996–2008.

In order to estimate per capita generation of household waste in Rio de Janeiro city up to 2030, we adopted the growth trend of this index provided by the dispersion of the real data from 1995 to 2009 (COMLURB, 2010), according to which it will rise at the end of the study period to 0.916 kg/capita/day. Similar to the state of RJ, from these data, we estimated the solid waste generation and gravimetric compositions, adopting functions as shown in Fig. 3.

For the estimation of industrial waste, just as for the state of RJ, we considered as the best hypothesis the first-degree function,

[7] Large generator is who produces more than 31.7 gallons of waste per day, for example, shopping malls and supermarkets.

[8] Waste disposed in landfills by private enterprises upon payment of a fee charged by weight.

[9] Composed in general by manufactured products with expired sell-by date or which have not passed quality controls.

Table 7
Evolution of household per capita and industrial waste deposited in Rio de Janeiro city landfills.

Year	Household waste (kg/capita/day)	Industrial waste (10^3 ton)
2005	0.807	40.2
2010	0.842	64.5
2015	0.860	82.0
2020	0.878	104.2
2025	0.897	132.5
2030	0.916	168.5

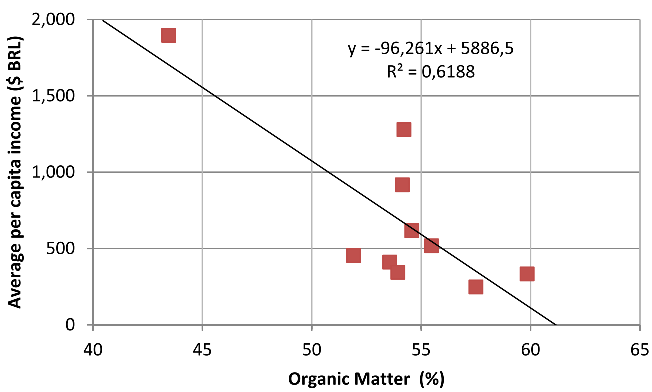

Fig. 4. Percentage of organic matter in waste by per capita income of the planning areas of Rio de Janeiro city.

according to the city's industrial production. Table 7 shows the evolution of these generations.

The waste composition data were obtained from the municipal historical series of COMLURB (2009), adapted to the classification recommended by the IPCC. The percentage of organic material, the portion with greatest responsibility for the generation of methane, was composed mainly of food scraps and bones. Since there is no clear trend, this percentage was estimated as a function of average per capita income in the city planning areas (IPP, 2010), which more clearly shows a decrease with increasing average incomes, according to Fig. 4.

Considering the average per capita income in 2000 of BRL 740.54[10] (IPP, 2010), substituting this value in the approximate equation of the line graph in Fig. 4 produces an organic matter content of 53.46%, a value close to the real figure (51.27%). But, based on the average annual per capita income growth in the city from February 2002 to September 2010 (annual average rate of 1.64%), average per capita income in 2030 will be BRL 1207.86, equivalent in the chart above to an organic matter level of 48.60%, which is consistent with other estimates of growth of the city.

Selective collection in Rio de Janeiro City accounts for less than 0.4% of the total waste generated in the city, amounting to about 6000 tonnes/year of household waste, where only "paper" is included in the calculation of methane emissions, whose reduction is negligible.

1.2. GHG emissions – Brazil, Rio de Janeiro state and city inventories

According to the Second Brazilian Inventory of Greenhouse Gas Emissions (MCT, 2010), solid waste was responsible for emitting 1.2% of total emissions in the country.

[10] The exchange rate of Brazil's currency, the Real (BRL), against the US Dollar, since 1999 when Brazil floated its currency has ranged from over slightly over BRL 3.00 at its weakest to just under BRL 1.60 at its strongest. It is currently around BRL 2.05.

Table 8
GHG emissions from Brazil, RJ State and Rio de Janeiro City in 2005.

Geographical area	$GgCO_2$	$GgCH_4$	GgN_2O	$GgCO_2e$
Brazil	109.9	1,104.2	6.8	25,417.2
RJ State	25.0	192.4	0.0000053	4,064.4
Rio de Janeiro City	0	76.5	0	1,604.6

In terms of Brazil, the relative share of waste management is small in GHG emissions, but in terms of methane, it is very important, accounting for 6.1% of total emissions in the country, accounting for 63.3% of waste emissions. Waste management contributed minimally to emissions of CO_2 due to burning carbon-containing non-renewable materials, with 0.4% of solid waste emissions. With respect to N_2O, it accounted for 8.3%. When it comes to state inventories and large population centers, such as state capitals, its share in emissions becomes more relevant, as shall be seen. According to the Rio de Janeiro State Inventory of GHG Emissions (Rovere et al., 2007), solid waste was responsible for the emission of 5.8% of total emissions in the state. Household waste was responsible for most of these emissions, contributing 91.3% of solid waste emissions. Therefore, the emissions from ISW accounted for 8.7% of these emissions. In Rio de Janeiro city, methane recuperation was not considered because according to the method adopted, estimated emissions in 2005 were the sum of the contributions of the last 30 years, during which there was only capture and flaring, with no incineration plants.

In Rio de Janeiro city, the waste sector was the second largest source of GHG emissions, representing 21.0% of total municipal emissions, second only to the energy use sector, with 73.6%. Solid waste subsector (part of the waste sector) accounted for the second largest source of emissions of subsectors in Rio de Janeiro city, corresponding to 14.1% of total emissions, behind only emissions from light road transport (part of energy use sector), corresponding to 26.2% of total emissions in the city.

The contribution of industrial waste to total emissions in the city of Rio de Janeiro was only 2%.

Table 8 presents the inventory results for GHG emissions in the geographical areas in study.

2. Methodology for future scenarios

The purpose of scenarios is to give, to the extent possible, clear and consistent possibilities for the future, without the intention of making predictions. They should be interpreted as simple estimates of what can happen, projected from hypotheses about relevant variables to the behavior of a system under study. The scenarios should be considered as possible paths toward the future and a way to increase understanding of the consequences of potential events and long-term policies, at a certain level (Rovere et al., 2006).

The construction of the basis of a prospective scenario goes through several phases, including definition of the system studied, diagnosis of the current situation and examination of its past evolution. From the construction of this baseline, the prospective part itself starts, subdivided into the following phases: development of a trend scenario and contrasted scenarios; and description of what can happen in various periods that make up the horizon considered. Fig. 5 presents the quantification of GHG emissions in RJ State that can be estimated and their reductions that can be achieved with the adoption of alternative scenarios compared to the baseline scenario A.

Both for Brazil and for the state and city of Rio de Janeiro, Scenario A was defined by the continuation of trends observed in

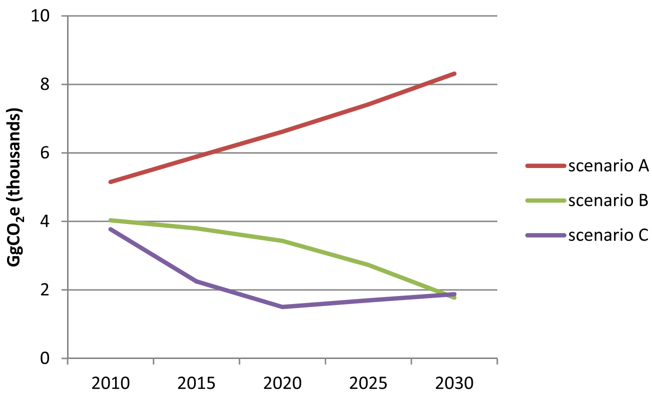

Fig. 5. Estimating emission reductions for different scenarios in RJ State.

Table 9
Annual growth rates (%) according to socioeconomic assumptions adopted. *Sources:* IBGE (2008), IBGE (2011), IPP (2008), IPP (2010) and SEDEIS-RJ (2008).

Rates	Brazil	RJ State	Rio de Janeiro City
Population (2006–2008)	0.70	0.90	0.26
Population (2009–2010)	0.45		
Population (2011–2015)	0.59		0.38
Population (2016–2020)	0.48	0.80	0.48
Population (2021–2025)	0.39	0.70	
Population (2026–2030)	0.27	0.60	
GDP (2011–2020)	4.50	4.10	4.92
GDP (2021–2030)	3.60		
Industrial GDP (2008–2012)	4.50	5.00	9.87
Industrial GDP (2013–2020)		6.00	
Industrial GDP (2021–2030)	3.60		

2005, as inventoried in 2005. Therefore, to project the allocation of the different types of waste treatment, we assumed the proportion would continue to be the same as that observed. Furthermore, since Scenario A is counterfactual, we considered there to be no additional capture of methane, so as to represent a scenario in which no intervention is made to minimize GHG emissions.

For Scenario B, the trajectory of growth in waste generation is identical to Scenario A, but actions and measures that reduce GHG emissions are included. These actions are part of the public planning and policy for the sector expected to be implemented over the study horizon.

Scenario C includes the most optimistic technological options for reducing GHG emissions. Like Scenario B, the growth trajectory of waste generation remains identical to Scenario A, but all possible actions and measures currently in the preliminary evaluation or planning stage are considered to be successfully adopted by the public authorities.

2.1. Methodological approach and future estimates

To estimate the GHG emissions from municipal solid waste in this work, based on observed figures for 2005 and projections for future scenarios on the horizon to 2030, we adopted the first-order decay method, established in the guidelines for national greenhouse gas inventories from the Intergovernmental Panel on Climate Change (IPCC, 2006). The method distinguishes between the categories of disposal and the waste treatment in accordance with the physical nature of the residue responsible for the generation of greenhouse gases (i.e., landfill, incineration, composting, etc.).

In the absence of more specific information, we used the IPCC default values for all scenarios, such as the oxidation factor (OX) and the fraction of degradable organic carbon that actually degrades (DOCf).

The oxidation factor (OX) is related to the fraction of landfill gas that undergoes spontaneous combustion in disposal sites and does not generate methane, which varies from 10% to 0% depending on the type of landfill (dump, controlled, and sanitary).

The DOCf depends on many aspects, such as temperature, moisture, pH, and gravimetric composition. Because the anaerobic degradation process may be incomplete, the IPCC considers that half of the carbon is not emitted, or part of the organically degradable carbon takes too long to degrade, and thus suggests a value of 50%.

The good practices manual of the IPCC (2006) recommends the use of waste disposal data going back at least 50 years to provide acceptable results for most practices and conditions of disposal. However, here, we chose 30 years since in this period, the risk of underestimating emissions is virtually nil. As the last year inventoried was 2005, to estimate GHG emissions from this year, it was necessary to consider the data and estimate waste generation since 1975.[11]

For the construction of scenarios, it was necessary to project the waste generation and its allocation among the different forms of management. For this, we considered the projected economic and population growth. As for class II-A ISW, we assumed the same disposal and composition as for household, and therefore, the estimate of emission follows the same method.

With regard to incineration, the masses of MSW, ISW, and HSW were projected from the data from the Brazilian Association of Public Sanitation and Special Waste Disposal Companies (ABRELPE, 2010) and the Second National Emissions Inventory conducted by the Ministry of Science and Technology (MCT, 2010), considering that the growth of these residues over time will also be proportional to GDP growth.

As for the cost abatements, these were estimated for systems of methane destruction in landfills and used estimates of the Low Carbon Study for Brazil (World Bank, 2010). According to this study, the cost to deploy a landfill in Brazil is BRL 30.00 per capita and of a landfill to capture methane gas is BRL 56.00 per capita, considering an expected lifetime of 20 years for these facilities.

Table 9 shows the summary rates used in the estimates to construct the future scenarios for Brazil, Rio de Janeiro state and city up to 2030.

2.2. General policy directions – mitigation actions

2.2.1. Brazil

The "National Policy on Solid Waste" was the basis to develop the steps in planning by the federal government to reduce GHG emissions in Brazil, but this policy has no specific actions with targets and timelines for the waste sector, either for the management of solid waste or for energy recovery or gases generated. Thus, in scenario B, we considered the expansion of services for collection and disposal in landfills, increasing linearly from 2010, reaching 100% in 2030. The expansion of services in scenario C is the same as B, with capture and burning of methane generated, increasing linearly from 2010, reaching 100% in 2030 (Rovere et al., 2011).

2.2.2. The state of Rio de Janeiro

The Rio de Janeiro state government has established some measures to reduce GHG emissions. These are considered in Scenarios

[11] The historical series of data from the cleaning company of Rio de Janeiro City has data since 1981. To get to 1975, we just forecast the trend retroactively. For the State and the Country, we did the same on the basis of historical data on population, GDP and HDI, based on official information from statistical agencies of the State of Rio de Janeiro and Brazil, respectively.

Table 10
Emissions and reduction potential of future scenarios for the solid waste sector in Brazil ($GgCO_2e$).

Scenario	2010	2015	2020	2025	2030
A	38,759	48,172	53,493	55,703	54,915
B	38,759	48,852	55,634	61,996	65,569
C	38,759	47,232	48,609	43,901	33,715
A–B	0	−680[a]	−2,142	−6,293	−10,654
%	0%	−1.4%	−4.0%	−11.3%	−19.4%
A–C	0	940	4,883	11,803	21,200
%	0%	2.0%	9.1%	21.2%	38.6%
B–C	0	1,620	7,025	18,095	31,854
%	0%	3.3%	12.6%	29.2%	48.6%

[a] Negative reductions correspond to increased emissions.

B and C, among which are the "State Plan for Integrated Solid Waste Management" (PEGIRS) and optimization of the processes for licensing by its environmental control agency (INEA). The list of actions considered to reduce emissions in the state of Rio de Janeiro for scenario B is as follows:

- all the waste of the state will be sent to waste treatment plants (CTRs), and controlled landfills and garbage dumps will be closed gradually by 2030;
- increase in waste collection to 100% in 2030;
- Adrianópolis CTR – 10,000 m^3/h LFG (80% captured in 2010);
- gradual increase in the methane recovery to 80% in 2030;
- burning of biogas recovered in CTRs in flairs.

For Scenario C, we considered the measures established by Decree 43,216 of September 30, 2011, which regulates State Law 5690 of April 14, 2010, establishing the "State Policy on Global Climate Change and Sustainable Development" in accordance with the "State Pact for Sanitation Program" (Decree 42,930 of April 18, 2011). Below is the list of actions considered to reduce emissions in the state of Rio de Janeiro for scenario C:

- emissions reduced by 65% compared to 2005;
- eradicate the use of landfills within the state by 2014 (Zero Dumping Program);
- remediation of existing dump sites by 2016 (Zero Dumping Program);
- continued growth of energy generation from waste.

2.2.3. Rio de Janeiro city

The Rio de Janeiro municipal government established the following measures to reduce GHG emissions, considered in Scenario B:

- Seropédica CTR to start operation in January 2012;
- selective collection (recycling) 5%;
- Gramacho landfill closes in January 2012 and will collect 1800 m^3/h biogas from June 2009 and 80% in March 2012 goes for industrial use;
- Gericinó landfill closes in December 2011 and will collect 70% of biogas from January 2014;
- collection of 80% of the biogas for burning in Seropédica CTR from January 2012;
- production of 7500 m^3 of composting compound (equivalent to 7.66 Gg/year of waste) from 2010.

Finally, the measures to reduce GHG emissions in Rio de Janeiro city, considered in Scenario C, were as follows:

- Seropédica CTR to start operation in January 2012;
- selective collection (recycling) 10%;
- Gramacho landfill, even closed, will increase biogas collection for industrial use to 85%;
- Gericinó landfill, even closed, will increase biogas collection for industrial use to 85%;
- collection of 85% of the biogas for burning in Seropédica CTR;
- production of 15,000 m^3 of composting compound (equivalent to 15.33 Gg/year of waste) from 2011.

3. Potential emissions reduction

3.1. Brazil

The results presented in Table 10 show that the solid waste management in Brazil,[12] including the disposal of industrial waste in landfills and incineration of waste, will emit 14% more in 2030 in relation to 2015 if no mitigation actions are taken. In Scenario B, up to 2015 emissions from solid waste exceed the level in Scenario A due to expansion of services for collection and disposal in landfills, reaching 34% more in 2030 in relation to 2015. However, in Scenario C, emissions are just reduced by 2% in 2015, arriving in 2030 at 30% less CO_2e in relation to 2015, due to the expansion of waste management services along with the recovery of methane (Rovere et al., 2011).

3.2. The state of Rio de Janeiro

The results presented in Table 11 show that solid waste in the State[13] is responsible for emitting 61% more in 2030 in relation to 2010 if no mitigation actions are taken. In Scenario B, in 2010 emissions from solid waste fall just over 4 million tonnes of CO_2e, with a further decline of 56% in 2030, in relation to 2010. In Scenario C, the amount of emissions is lower than in Scenario A, but slightly exceed 2030 emissions in Scenario B, due to the economic growth, despite the expansion of collection services and treatment of waste with the recovery of methane.

3.3. Rio de Janeiro city

The results presented in Table 12 show that GHG emissions in the city of Rio de Janeiro[14] can rise 7% in 2030 in relation to 2010 if no mitigation actions are taken. In both scenarios B and C in 2010, emission reduction is small, but by 2015, the reduction is substantial, with the closure of old landfills and opening of the Seropédica Waste Treatment Center, which from the start will have technology for destruction of methane, just as in old landfills, where the system is installed after the end of operation. Thus, in 2015, there is a 77% reduction in these emissions in Scenario B and 84% in Scenario C, in relation to 2010, with the same general trends holding in the estimate for 2030, although slightly higher in function of the estimated economic growth.

[12] The Brazilian population growth projection was obtained from municipal population estimates, based on the results of the last census in 2010 (IBGE, 2011). Based on this information and the per capita generation, we estimate the future generation of waste. For GDP, the projection was made using annual rates, analogously to industrial GDP. The masses of HSW and MSW incinerated were projected also considering the increase of this quantity over time in proportion to GDP growth.

[13] To the future population and the industrial GDP annual growth of the State of Rio de Janeiro, was used the Energy Mix Study for 2008-2020 (SEDEIS-RJ, 2008); to the GDP growth rate, was used the IBGE (2008).

[14] In Rio de Janeiro city, was used the Demographic Trends Study in the City (IPP, 2008), which provides the population projection from 2000 to 2020. For the period from 2020 to 2030, was used the rate estimated for 2020. To estimate the GDP growth rate, were used the figures presented by IPP (2010). The growth of industrial GDP for the municipality was the rate observed in 2007.

Table 11
Emissions and reduction potential in future scenarios for solid waste in the state of Rio de Janeiro ($GgCO_2e$).

Scenario	2010	2015	2020	2025	2030
A	5,152	5,890	6,620	7,415	8,314
B	4,032	3,797	3,432	2,729	1,774
C	3,771	2,248	1,501	1,695	1,874
A–B	1,120	2,094	3,188	4,685	6,540
%	21.7%	35.5%	48.2%	63.2%	78.7%
A–C	1,381	3,642	5,118	5,720	6,440
%	26.8%	61.8%	77.3%	77.1%	77.5%
B–C	262	1,548	1,931	1,034	−100
%	6.5%	40.8%	56.3%	37.9%	−5.6%

Table 12
Emissions and reduction potential in future scenarios for solid waste in Rio de Janeiro city ($GgCO_2e$).

Scenario	2010	2015	2020	2025	2030
A	1,803	1,817	1,855	1,894	1,934
B	1,680	377	373	376	383
C	1,678	263	268	273	280
A–B	123	1,440	1,482	1,518	1,551
%	6.8%	79.2%	79.9%	80.1%	80.2%
A–C	125	1,554	1,587	1,621	1,654
%	6.9%	85.5%	85.6%	85.6%	85.5%
B–C	2	114	105	103	103
%	0.1%	30.2%	28.2%	27.4%	26.9%

4. Costs of abatement actions

The costs in the scenarios constructed are related to typical actions for the treatment of solid waste, which is the destruction of methane produced in landfills by the decomposition of wastes. These costs were obtained from the Low Carbon Study for Brazil (World Bank, 2010) and specifically in the management of waste from the São Paulo State Sanitation Company (CETESB, 2012), so the calculations relate to the differences from these actions between Scenarios A and B, A and C, B and C. It should be noted that we used a social discount rate of 8%[15] for the period. The exchange rate used in the study was BRL 2.20/USD 1.00.

Table 13 shows the estimated total abatement costs at present costs of implementing mitigation of GHG emissions in Scenario B and C compared to A for Brazil, RJ state and RJ city.

For both Scenario A and Scenario B, the total investment cost in Brazil for collection and disposal of waste in landfills, and implementation of systems for capture and destruction of methane, as projected in Scenario C, would be approximately USD 2.25 billion (Rovere et al., 2011). For the state of Rio de Janeiro, this cost is USD 372 million, and for the city, the cost is USD 131 million. These figures refer to total expenses every year, according to the total abatement costs over time shown in Fig. 6.

5. Analysis of the results

The necessary investments in solid waste management in Brazil and the State and the City of Rio de Janeiro are presented in Table 14.

In the State and the City of Rio de Janeiro, when relating scenario B with C, the average cost rises in Scenario C because of the lower emissions assumed if compared to B.

[15] Value considered as the social discount rate for projects in Brazil (World Bank, 2010).

Table 13
Total abatement costs for mitigation of GHG emissions (USD million).

Geographic Area	2010	2015	2020	2025	2030
Brazil[a]	13.44	99.81	129.63	130.21	117.20
State of RJ	2.22	16.52	21.46	21.56	19.40
Rio de Janeiro City	0.79	5.83	7.57	7.60	6.84

[a] There is no estimate of cost abatement stage B to A with respect to Brazil, since there is an increase in emissions, since the emission B are larger than those of A (see Table 16).

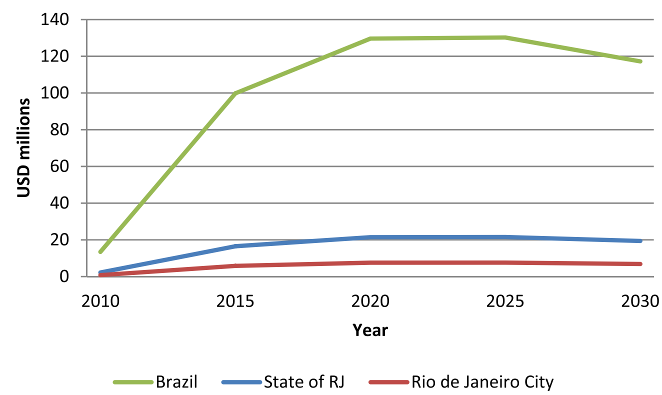

Fig. 6. Change of the total abatement costs of solid waste sector in Brazil (USD millions).

Table 14 – Potential emission reduction in solid waste (million tonnes CO_2e) and associated costs (US$ per tonne CO_2e) in the geographic areas.

With respect to the potential for use of biogas to generate electricity, based on the results for emissions avoided in this study, considering that the thermodynamic efficiency of a generating plant varies from 30% to 50% (we used 30% to be conservative) and that the lower calorific value of natural gas is 9256 kcal/m^3, and assuming that natural gas is composed of 94% methane, with a density of 0.716 kg/m^3, and that 1 kW h corresponds to roughly 861.2 kcal in physical terms, then, it is possible to calculate the electrical potential from methane recovered in MW h, from 2010 to 2030. Based on this quantity of electricity not drawn from the grid, we calculated the emissions avoided by generation using this renewable energy source, adopting the emission rate from the electricity generated in the South, Southeast and Midwest regions of Brazil, which according to ONS (2011) is 261.1 tCO_2e/GW h.

Table 15 shows a summary of the potential to generate electricity from solid waste in Brazil as well as the state and city of Rio de Janeiro, over the 20-year study period, as well as the revenues derived from sale of this renewable energy and from Certified Emission Reductions (CERs or carbon credits) from burning methane at sanitary landfills and thus not drawn from the power grid.

In Brazil, electricity tariffs charged by generators are set by the National Electric Energy Agency (ANEEL) through auctions. In the last auction, the gas-fired thermoelectric generators presented offers of BRL 100.00/MW h, and wind farm operators offered BRL 91.00/MW h. The offers by hydroelectric projects in the Amazon region, all of which will be large when built, were lower still. In turn, the rates charged to residential consumers can reach BRL 500.00/MW h in many states (including transmission, subtransmission, and distribution costs as well as taxes and profits).

In general, energy generation from biogas produced by solid waste would be competitive if fed into the national power grid at a price of BRL 100.00/MW h or less. Therefore, we can consider waste treatment centers as gas-fired generation plants and adopt this value.

Table 14
Potential emission reduction in solid waste (million tonnes CO_2e) and associated costs (US$ per tonne CO_2e) in the geographic areas.

Geographic Areas	Avoided Emissions (10^6 ton CO_2e)	US$/ton CO_2e	Scenarios
Brazil[a]	−76.7	0.0	B/A
	224.1	***10.03***	***C/B***
State of RJ	72.3	5.15	B/A
	96.8	***3.84***	***C/A***
	24.6	15.16	C/B
Rio de Janeiro City	27.8	4.97	B/A
	29.8	***4.64***	***C/A***
	2.0	70.63	C/B

[a] *Source:* Rovere et al. (2011), Authors.

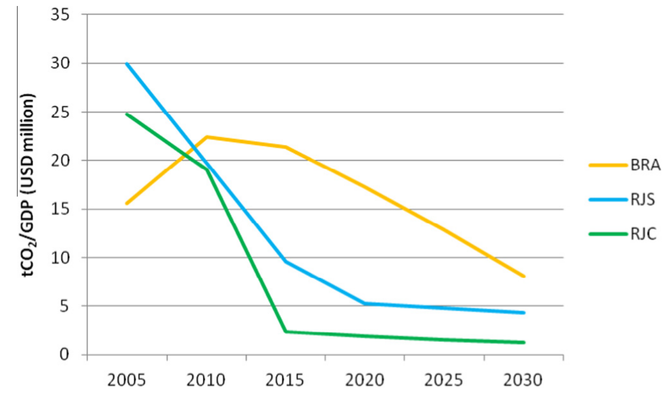

Fig. 7. Comparison of emission intensities in scenario C as a function of GDP growth for Brazil, Rio de Janeiro state and Rio de Janeiro city.

By adding up all the investments directed to the maximum potential of emission reduction and discounting all possible gains from revenues from the sale of carbon credits from burning methane in landfills and avoided electricity on the grid, it was possible to determine their respective balances. Table 16 presents a summary of the maximum potentials for reducing emissions of greenhouse gases generated by solid waste management in the three geographic areas covered in this study and their respective balances.

Finally, we compare the future emissions among the three areas, through indexes of intensity compared to GDP and population growth. That is the only way to compare the evolution of scenarios C between geographical areas, since these areas scales are quite different. Figs. 7 and 8 show the evolution of these indexes.

Comparing the three geographical areas under study, we can say that Brazil as a whole will present the worst intensities, both in terms of GDP and population. The best index is Rio de Janeiro city's, while the state is always at an intermediate level between 2015 and 2030.

Keeping the evolution trends of emissions intensity from 2030 onwards, it is possible to see a convergence of decreasing rates by GDP in the three geographic areas. It is recommended to check in the future if these results were due to the emissions reductions calculations or if the projected growth of GDP for the period was overestimated.

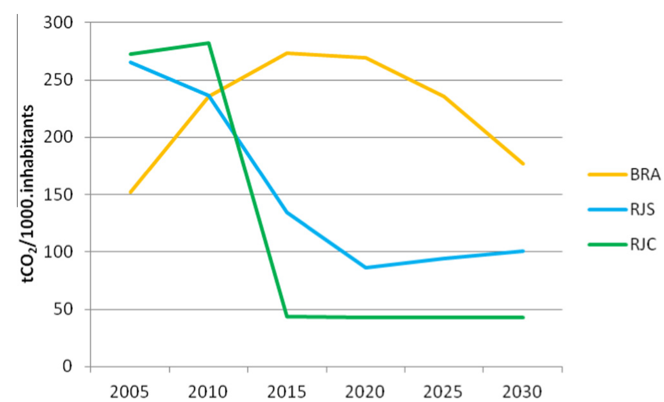

Fig. 8. Comparison of emission intensities in scenario C as a function of population growth for Brazil, Rio de Janeiro state and Rio de Janeiro city.

Regarding intensities according to population, the curve representative of Brazil presents a sharp drop from 2020, which bodes well for the future, but in the case of Rio de Janeiro state, the trend

Table 15
Potential generation of electricity and revenues[a] of emissions reduction from methane destruction and waste energy in geographic areas. *Source:* Authors.

Geographic area	Revenue of CERs from methane destruction in landfills (10^6 USD)	Potential energy generation (10^3 MW h)	Revenue from sale of energy generated (10^6 USD)	Emissions avoided from energy generation (10^3 tCO2e)	Revenue of additional CERs from energy (10^3 USD)
Brazil	1,631.7	1,009.4	55.45	263.5	1,918.6
State of Rio de Janeiro	705.0	436.1	23.96	113.9	829.0
Rio de Janeiro City	216.9	134.0	7.36	35.0	257.2

[a] The carbon credit exchange rate used in the estimates was USD 7.28 per tonne of CO_2 avoided, and the exchange rate of the Brazilian currency, the Real (BRL), against the US Dollar (USD), was BRL 1.8203, both in values of March 27, 2012 (Forexpros, 2012).

Table 16
Maximum potential emission reduction, associated costs and revenue balances of solid waste management in the geographic areas.

Geographic Areas	Comparison between Scenarios	Avoided Emissions (10^3 ton CO_2e)	Total Cost (10^6 USD)	Total revenue (10^6 USD)	Balance (10^6 USD)
Brazil	C/B	224,138.8[a]	22,48.1[a]	1,689.1	−559.0
State of RJ	C/A	96,843.3	372.1	729.8	357.7
Rio de Janeiro City	C/A	29,795.8	138.3	224.5	86.2

[a] *Source:* Rovere et al. (2011) and Authors.

over the last 10 years of the study period is up, which may indicate the need to expand efforts to reduce GHG emissions. In Rio de Janeiro city, the trend is stationary from 2015 until the end of the study period.

6. Conclusions

The participation of solid waste management in greenhouse gas emissions in Brazil reflects the large liability left by mistaken waste management policies in the past, where open dumping is still the predominant way of disposing of solid waste. This is due to the fact that the collection, transportation, and disposal are prerogatives of municipal administrations, which do not always have technical and financial means to solve this problem, even when joining together with neighboring municipalities. But emissions from solid waste in Brazil will rise as access to collection and treatment services expands. This is because the appropriate management of waste involves the use of anaerobic treatment systems in the country. This can be circumvented by adopting or increasing the efficiency of methane recovery projects with burning or processing of biogas, to help reduce emissions.

Hence, based on the results obtained in this study, it is possible to say that the negative impacts of climate change have created a huge opportunity for Brazil to expand its infrastructure for municipal solid waste management. Despite the costs involved in implementing the various mitigation actions evaluated in this work, the potential revenue from products of solid waste processing technology likely to be implemented, either by credit trading in the global carbon market or energy sales for local supply, is more than sufficient to make large enterprises economically feasible, transforming the current scenario of solid waste management in the country into one of financial and environmental gains.

In the case of the city and state of Rio de Janeiro, sale of carbon credits (CERs) would suffice to make the costs for landfills treatment (and methane destruction) economically viable, something that does not hold for whole Brazil. Nevertheless, the gains from sale of the electricity generated from biogas are much greater, more so when including revenues from CERs for burning methane and also from avoided emissions.

The recently adopted "National Solid Waste Policy" (specified in Federal Law 12,305/2010) and "National Climate Change Policy" (Federal Law 12,187/2009) and the climate change policies adopted by the state of Rio de Janeiro (Decree 43,216/2011) and city of Rio de Janeiro (Municipal Law 5248/2011) together will mean stepped up efforts, helping to overcome old problems of insufficient funds allocated to landfills.

With the follow-up to the United Nations Conference on Sustainable Development – Rio +20, the drafting of new global targets to reduce emissions and rules on carbon taxation or other economic measures at the level of countries is expected. In this respect, an example was set at the City Dome – C40, a parallel event to Rio +20, where 40 mayors from Rio de Janeiro state approved a joint commitment with goals to reduce GHG emissions. If enforced, these commitments would make inadequate management of waste impractical financially to Brazilian states and municipalities.

It should be recalled that the Brazil Low carbon Country Case Study from the World Bank (2010) did not consider the costs of building and operating thermoelectric generation plants (landfill gas use), instead only considering the costs of building and operating treatment centers at sanitary landfills to capture and burn methane. Nevertheless, it is still possible to state that the gains from sale of the energy are greater than the costs of installing a thermoelectric plant, making it feasible to invest in this technology, considering the current Brazilian scenario for management of solid waste.

Nowadays, there are many different procedures and technologies to treat solid waste, but in Brazil, landfilling seems to be a good solution for waste treatment in the coming years, to the extent that more economical and environmentally adequate solutions are not possible to implement. However, it is not easy to convince the population to accept the construction of a nearby landfill (the "not in my backyard" syndrome). So, thermal, mechanical, and biological treatment and other procedures need to be discussed as concrete possibilities to solve Brazil's solid waste problem in the future.

Since solid waste has several applications, especially energy generation, either directly by burning or indirectly as fertilizer for oilseed cultivation to produce biodiesel and charcoal, it is important to identify which technologies can be applied in the state of Rio de Janeiro, and particularly in the city of Rio de Janeiro, to optimize management practices in function of quantity available, composition, possibility of using byproducts in rural areas and the associated revenues and expenses.

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