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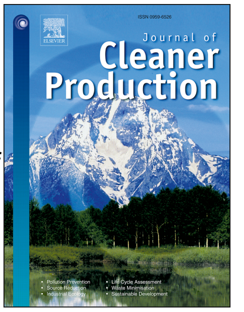

Carbon accounting approaches and reporting gaps in urban emissions: An analysis of the Greenhouse Gas inventories and climate action plans in Brazilian cities

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Materials & Methods

Content Analysis of:

- 24 Greenhouse Gas (GHG) Emissions Inventories of Brazilian Cities;
- Climate action plans for 11 cities;

Carbon Acccounting Approach Used:

Production-Based Carbon Accounting

Sectors Measured:

- Stationary energy + Electricity (all cities)
- Transport (all cities)
- Waste (all cities)
- Industrial process and Product Use (4 cities)
- Agriculture, Forestry and other Land Use (7 cities)

Gaps Identified

Gap 01: Incompleteness Gap
(17 reports)

GHG Reports did not account GHG emissions of all economic sectors/subsectors. Relevant emission sources may be neglected.

Gap 02: Lack of Transparency
(20 reports)

It is not possible to assess the accuracy of the GHG results because input data, emission sources; emission factors or calculation methodologies were not disclosed.

Impacts on Climate Plans

No climate action plan considered mitigation actions regarding consumption patterns of the city and initiatives for sustainable consumption

Actions to overcome the gaps

Gap 01

- To identify main economic activities, consumption patterns and emission sources considering both approaches PBA and CBA;
- To assess the necessary data to emission calculation;
- To analyze the feasibility of data collection;
- To decide about carbon accounting approach, boundaries sectors and subsectors to be measured;
- To use more robust information system that allow an integrated production-consumption.

Gap 02

- To identify clearly boundaries, sectors and sub-sectors included in the GHG inventory;
- To justify any exclusion;
- To present clearly assumptions, input data, source of input data, calculation methodologies and emission factors used for GHG emission calculation;
- To describe limitations and uncertainties of the report;
- To engage stakeholders on GHG inventory development with a more transparent and participatory process.

Carbon Accounting Approaches and Reporting Gaps in Urban Emissions: An Analysis of the Greenhouse Gas Inventories and Climate Action Plans in Brazilian Cities

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Abstract

This paper analyzes the differences among the main existing carbon accounting methodologies for cities and identifies the shortcomings in carbon inventories typically used. Data were collected from the GHG inventories and climate action plans from 24 Brazilian cities using content analysis. All cities developed their GHG inventories using Production-Based Approach (PBA), adding at least electricity and waste emissions that occurred out-boundaries. Several gaps were identified in the cities' greenhouse (GHG) emissions inventories that consequently impacted their climate action plans. Two main types of reporting gaps were identified: incompleteness (Gap 1) and lack of transparency (Gap 2). Seventeen GHG reports presented Gap 1. Brazilian cities' GHG reports do not appropriately reflect emissions occurring as a result of activities and consumption patterns of the city. Twenty reports presented Gap 2 with no transparency about assumptions, input data, source of input data, emission factors, calculation methods or accounting limitations. Sixteen cities measured only (I) stationary energy, including electricity imported by the grid; (II) transport; and (III) waste. Four cities reported also Industrial Process and Product Use (IPPU) emissions and seven, reported Agriculture, Forestry and other Land Use (AFOLU) emissions/removals. Brazilian cities did not measure GHG emissions related to consumption of foods, beverages and imports of manufactured products. As a result, no climate action plan considers actions towards sustainable consumption. The study provides insights for academics and policymakers on how to choose the best methodology and develop more complete inventories and low-carbon plans.

Key Words: Carbon accounting for cities; Carbon accounting approaches; Consumption-based carbon accounting; Production-based carbon accounting; GHG emissions inventories gaps, Climate action plans.

1. Introduction

Several studies show that the approach used in the accounting of Greenhouse Gases (GHG) can significantly impact the results of the GHG inventory in cities (e.g. Sudmant et al., 2018; Andrade et al., 2018). Depending on the carbon accounting approach adopted, some GHG emission sources may be neglected or underestimated. Thus, the accounting method shapes the provision of the information, and consequently may limit public policies to combat climate change (Harris et al., 2012).

Existing studies have suggested that, depending on the economic profile of the city, the results of consumption-based emissions inventories (CBA) can be much larger than those of production-based approach (PBA) inventories (e.g. Sudmant et al., 2018; Andrade et al., 2018). There are authors that support the use of CBA approach (Dodman, 2009; Harris et al., 2012; Lombardi et al., 2017; Andrade et al., 2018), while others argue that PBA should continue to be the standard given the uncertainties, technical difficulties and lack of data required to reliably use the CBA approach (Peters, 2008; Afionis et al., 2017; Franzen & Mader, 2018).

Several authors discuss the impact of the carbon accounting approach on GHG results (e.g. Dodman, 2009; Harris et al., 2012; Lombardi et al., 2017; Sudmant et al., 2018; Andrade et al., 2018). Some recent research also proposes methods to improve the comprehensiveness and accuracy of carbon accounting for cities (Li et al., 2017a; Liao et al., 2017; Shan et al., 2017; Cai et al., 2018; Ottelin et al. 2018; Mi et al. 2019).

Emissions data based on inventories are foundations of climate change mitigation research and actions. However, studies focusing on the quality analysis of cities GHG reports are rare. It was not found in the literature any paper that specifically analyzes the gaps of the cities GHG accounting reports (hereafter referred as "gaps") and their climate action plans.

According to Li et al. (2017b), research and practices related to city-level GHG inventories are relatively limited, especially in developing countries. Castán Broto & Bulkeley (2012) and Van der Heijden (2019) also mention that existing literature about cities responses to climate change is focused on individual case studies or small set of cities in more economically developed countries.

Brazil is one of the world's largest economies and one of the top ten highest GHG emitters in the world (Carbon Brief, 2018) providing a good case to examine the kind of methodologies used by cities and the shortcomings of their reports. It is a highly urbanized country with more than 85% of its population living in cities. Twenty-four Brazilian cities have already developed GHG inventories representing 27.4% of Brazilian GDP and almost 20% of Brazilian population (more than 40 million people). The understanding of how Brazilian cities measure GHG emissions and their GHG reports gaps can bring lessons to improve the way cities collect GHG information and increase the quality of climate action plans.

This paper has some objectives both to fill the gaps in the scientific literature and provide useful guidance for practice. Firstly, it intends to contribute to the literature in comparing the different GHG methodologies for cities in terms of coverage, efforts and usage. Secondly, the study identifies the main shortcomings of the GHG inventories in terms of quality and gaps (Mi et al., 2019; Mia et al., 2019) by assessing the inventories developed by Brazilian cities. Thirdly, the study analyzes how cities in the most populous country and largest economy of Latin America are combating climate change. Finally, the paper proposes some actions policy makers can take in order to overcome these gaps and improve the quality of the cities GHG inventories and climate plans contributing to the academic efforts to reduce uncertainties in cities emission inventories (Mi et al., 2019). This helps to broaden the scope of existing examples, mostly from developed countries as pointed out by the literature (Castán Broto & Bulkeley, 2012). The research also advances the way they can develop broader and more complete GHG inventories that may lead to more effective low-carbon plans, as well as make the city population aware of the importance of their production and consumption choices in relation to the climate.

2. Materials & Methods

A literature review was carried out and empirical data were obtained from documents issued by Brazilian cities and other secondary sources in 2018 and 2019. Even though no questionnaire was applied, the authors contacted the Latin American Secretariat of Local Government for Sustainability (ICLEI) by phone and e-mail to collect all GHG inventories of its members cities in Brazil in 2018.

Brazil is a good case to advance the literature on carbon inventories in cities in order to overcome the bias of previous studies towards developed countries (Castán Broto & Bulkeley, 2012). As a developing country, Brazil is one of the world's leading GHG emitter and the most populous and largest economy of Latin America.

ICLEI shared all GHG reports of Brazilian cities that developed their GHG inventory with ICLEI support. Once the reports were analyzed, the researchers contacted the Carbon Disclosure Project (CDP) - Latin America to collect data Brazilian cities submitted to CDP Cities and States & Region - Latin America. CDP is a platform cities can report their emissions inventories. The manager of the CDP Cities and States

& Region - Latin America provided access to answers that had been provided by Brazilian cities to CDP. Through this platform, researchers could find more detailed information about the GHG accounting of Brazilian cities and emission reduction plans. All information provided by Brazilian cities to the public platform Carbonn Climate Registry[1] was also collected and analyzed.

From 18 GHG inventories[2], 12 are open to the public. Two reports were shared by ICLEI with researchers (Porto Alegre and Betim). Three (Vitória, Niterói and Goiânia) were obtained through CDP and one (Duque de Caxias) was publicly available at the beginning of the research, but not anymore. All five climate action plans analyzed are publicly available.

The research team then carried out a content analysis of all GHG inventories and climate action plans developed by Brazilian cities. Based on the information from (I) the GHG inventories, (II) answers from Brazilian cities to CDP and (III) data supplied from Brazilian cities to Carbonn Climate Registry, it was possible to identify: (I) Carbon accounting approach followed by each Brazilian city and (II) sectors and emission sources included in GHG reports. Finally, we identified the gaps and limitations of each GHG inventory and classified the different kinds of gaps.

3. Theory: Literature Review of Carbon Accounting in Cities

3.1 PBA versus CBA

Existing GHG carbon accounting methodologies have two basic distinct approaches: the production-based approach (PBA) and the consumption-based approach

[1] http://carbonn.org/
[2] ABC Region GHG Report comprises 7 cities.

(CBA). While the former allocates GHG emissions to where they are generated in the production processes, the latter allocates the emissions to the final consumer.

Several studies show that the GHG accounting approach can significantly impact its GHG inventory results (Sudmant et al., 2018; Athanassiadis et al., 2018). Studies applying different approaches to GHG emissions inventories of New York, Paris and Shanghai found divergent results (Ibrahim et al., 2012). Other efforts also reached the same conclusion for London and Madrid (Andrade et al., 2018), Hong Kong (Harris et al. 2012) and 45 urban areas in China, the U.K. and the U.S. (Sudmant et al., 2018). Recently, several studies have discussed the impact of these methodologies on city-level carbon inventories and sub-national climate action plans (e.g. Larsen & Hertwich, 2010;Harris et al., 2012; Dahal & Niemala, 2017; Sudmant et al., 2018; Andrade et al., 2018; Athanassiadis et al., 2018).

Lombardi et al. (2017) define PBA as the methodology that includes all emissions from economic activities by resident companies and households. The PBA considers embodied emissions derived from the export city's activities. It assigns responsibility for emissions at the point where the emissions are produced.

Alternately, CBA measures the carbon emissions associated with the final consumption of goods and services. GHG emissions are calculated by subtracting the emissions associated with exported goods and services from PBA and adding those generated to produce imported goods and services (Grasso, 2016; 2017; Andrade et al., 2018; Sudmant et al., 2018). The CBA consists of emissions generated from the consumption of goods and services within an area regardless of where emissions from production of such goods and services have happened (Dahal & Niemelä, 2017). Therefore, this method includes emission sources that are beyond the boundary of the city (Lombardi et al., 2017). Example of estimations using CBA approach include Ottelin et al. (2018) and Liao et al. (2017). The first mapped consumption-based household carbon footprints to estimate carbon emissions of urban zones within Helsinki Metropolitan Area. The latter used an input-output model to measure the economic contribution of sectors and households to CO_2 emissions of Beijing.

Although the PBA is the most commonly used approach by cities around the world, several authors defend the CBA methodology. Both approaches have positive and negative aspects (see in Table 1). The key advantages of CBA include (I) eliminating carbon leakage, (II) covering more emissions, (III) consistency between consumption and environmental impacts and (IV) increasing mitigation options (Peters, 2008; Afinois et al., 2017; Andrade et al., 2018). Several authors agree that it is technically more difficult and uncertain to use CBA instead of PBA (Peters, 2008; Grasso, 2016; Franzen & Mader, 2018; Sudmant et al., 2018). CBA method requires more complex calculations, assumptions and estimations (Peters, 2008; Dodman, 2009; Afionis et al., 2017), while the PBA is much closer to the statistical sources. It includes domestic activities and is more consistent with the concept of gross domestic product (GDP) (Peters, 2008).

However, the two methodologies are not competing; rather, they are complementary. Ibrahim (et al., 2012), Lombardi et al. (2017), Andrade et al. (2018) and Athanassiadis et al. (2018) agree that a combination of these methods can be used. This combination would measure GHGs within city boundaries, plus indirect emissions deriving from infrastructure and non-infrastructure supply chains that serve the entire community.

Table 1: Main Advantages and Disadvantages of Each GHG Accounting Approach

GHG Accounting Approach	Advantages	Disadvantages	References
PBA	-Established reporting and widespread use; - Information used is closer to statistical sources; - Straightforward calculations; - Less uncertainty; -Consistency with political and environmental boundaries; - Government has more easily the authority to implement policies over the emissions.	- Coverage of only emissions generated inside the territory; - Lack consideration of emissions related to imported products and goods; - Motivation for carbon leakage; - Guiding ineffective mitigation policies.	Peters (2008); Dodman (2009); Grasso (2016); Afionis et al. (2017); Franzen & Mader (2018)
CBA	- Elimination of carbon leakage; - Coverage of emissions related to (I) imported products, materials, goods and services and (II) logistics of consumed products, materials and goods; -Consistency between consumption and environmental impacts; - Responsibility and fairness over consumption; - More precise diagnosis about the main emission sources of the cities; - Highlighting the impacts of a consumption lifestyle.	- Increase uncertainties; - Technical complexity; - Wider range of goods and services across the economy and across the borders should be considered; - Mitigation options can require political decisions outside the administrative boundaries and political influence.	Peters (2008); Dodman (2009); Larsen & Hertwich (2010); Grasso (2016); Afionis et al. (2017); Franzen & Mader (2018); Sudmant et al. (2018); Andrade et al. (2018)

Source: Developed by the authors

Some recent publications have proposed ways for constructing GHG emissions for cities using a combination of both approaches. Shan et al. (2017) proposes a PBA approach that estimates GHG emissions from Chinese cities through energy balance table. Li et al. (2017a) suggests a PBA approach by using sampling surveys, enterprise GHG reports and the spatial distributions. Cai et al. (2018) estimated emissions, using a PBA approach, establishing high spatial resolution dataset of CO_2 emissions of 286 Chinese prefecture-level cities in 2012.

Uncertainties of GHG inventories are high. Mi et al. (2019) argue that efforts are needed to reduce those uncertainties. Li et al. (2017b) mentioned problems in the Chinese cities inventories as incompleteness due to data unavailability, reporting problems and inconsistencies between the framework and the contents of the inventories. Andrade et al. (2018) mentions important sources of uncertainties associated to the Madrid's GHG emissions inventory as lack of disaggregated and high-quality data at a local scale.

Emission data are fundamental for guiding climate change mitigation research and actions. Although several papers provide methods to improve the comprehensiveness and accuracy of carbon accounting in cities, there are still uncertainties in these inventories. However, little effort has been made to identify and classify the gaps in a comprehensive manner based on the existing inventories and plans. The lack of consistent and comparable GHG emissions data at the city level is one of the four remaining gaps in the urban climate actions research area (Mi et al., 2019).

The only study found that explores the quality of GHG disclosures by cities is Mia et al. (2019). Their paper highlights that prior studies predominantly focused on corporate-level GHG disclosure and that there has been limited research, exploring cities' GHG disclosure. The manuscript then analyzes GHG disclosure of 42 cities published on CDP platform through the expectation gap framework. This paper is focused on reports of cities from C-40 international network and just discusses data provided by CDP. Details of cities GHG reports documents are not analyzed.

Castán Broto & Bulkeley (2012) says that research about cities responses to climate change has mainly focused on case studies or small sets of cities with a focus on members of specific transnational networks or early city pioneers. Van der Heijden (2019) also concluded that the empirical urban climate governance literature is still dominated by studies (and scholars) from the Global North, and it is still dominated by single-n and small-n studies. This fact has created a geographical bias towards cities in more economically developed countries.

3.2 Frameworks and Protocols

All GHG quantification protocols for cities derive their approaches and methodologies from 2006 IPCC guidelines (Andrade et al., 2018), which is based on the PBA approach. This methodology measures GHG emissions combining information of economic activity (called activity data, AD) (e.g., electricity and fossil fuel consumed) with coefficients that quantify the related emissions or removals per unit of activity (called emission factors, EF). GHG emissions are, therefore, calculated as follows:

Math Formulae 1: $\textit{GHG Emissions} = \Sigma AD_i \times EF_i$ *for each activity i.*

This method requires the reporting of direct emissions from sectors and subsectors and can also be applied at districts within the city's boundaries. Emission sources are generally classified into four sectors: (i) energy, (ii) industrial process and product use (IPPU), (iii) waste, and (iv) agriculture, forestry, and other land use (AFOLU).

Cities have become the object of recently developed methodologies, such as PAS 2070:2013 (PAS 2070) (Andrade et al., 2018). PAS 2070 specifies requirements for the assessment of the GHG emissions of a city using two distinct methodologies: (I) a direct plus supply chain (PAS 2070-DPSC) methodology and (II) a CBA methodology (PAS 2070-CB).

PAS 2070-DPSC includes PBA emissions plus emissions associated with the largest supply chains serving the cities, including water supply, food and drink, and construction materials, specifically cement and steel. PAS 2070-CB captures lifecycle GHG emissions for all goods and services consumed by the city. The PAS 2070-CB methodology sets out an approach to calculate the GHG emissions linked to global and national supply chains with the use of environmentally extended input output (EEIO) matrices.

Another protocol is the Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC), developed by a partnership between the World Resources Institute (WRI), the Local Governments for Sustainability (ICLEI) and the Cities Climate Leadership Group (C40) in 2014. The GPC requires cities to measure and disclose a GHG inventory using both production and consumption activities within the city boundary. It includes some emissions released outside the city boundary. It categorizes all emissions into 3 “scopes”, depending on where they physically occur (WRI, 2014), as follows:

- Scope 1: GHG emissions from sources located within the city boundary.
- Scope 2: GHG emissions from using grid-supplied electricity, heat, steam and/or cooling within the city boundary.
- Scope 3: All other GHG emissions that occur outside the city boundary.

GHG emissions from city activities shall be classified into six main sectors according to the GPC: (I) Stationary Energy; (II) Transportation; (III) Waste; (IV) Industrial Processes and Product Use (IPPU); (V) Agriculture, Forest and other Land Use (AFOLU) and (VI) Any other emissions occurring outside the geographic boundary as a result of city activities may be reported separately (WRI, 2014). These sectors are broken down by subsectors. Table 2 summarizes main carbon accounting protocols.

Table 2: Characteristics of carbon accounting frameworks

Characteristics	**Carbon Accounting Frameworks**			
	IPCC	**GPC**	**PAS 2070-DPSC**	**PAS 2070-CB**
Carbon Accounting Approach	PBA	PBA	PBA + largest supply chains	CBA
Sectoral division	Energy (including Transportation), Waste, IPPU and AFOLU	Stationary Energy; Transportation; Waste; IPPU; AFOLU and Other emissions out-boundary	Stationary Energy; Transportation; Waste; IPPU; AFOLU and Goods and Services	Food and Drink; Utility Services; Household; Transport Services; Private Services; Other Good and Services
Emission Subdivision by scopes	No	Yes	Yes	No

Source: Developed by the authors

4. Results and Discussions

4.1 Reports and Methodologies Used

Twenty-four cities reported their GHG inventories using the Carbonn Climate Registry or CDP databases (17 cities plus the ABC region, see Table 3) by may/2019. These 24 cities represent 27.4% of the Brazilian GDP and account for almost 40 million people, which is 19.7% of the country’s population. These cities are located in 12 Brazil states (see figure 1). Twelve cities are capitals of their states (i.e., Vitória, João Pessoa, Palmas, Recife, Goiânia, Fortaleza, Salvador, Porto Alegre, Curitiba, Belo Horizonte, Rio de Janeiro and São Paulo) and seven form the ABC region, which are part of the metropolitan area of the city of São Paulo: Diadema, Mauá, Ribeirão Pires, Rio Grande da Serra, Santo André, São Bernardo do Campo and São Caetano do Sul.

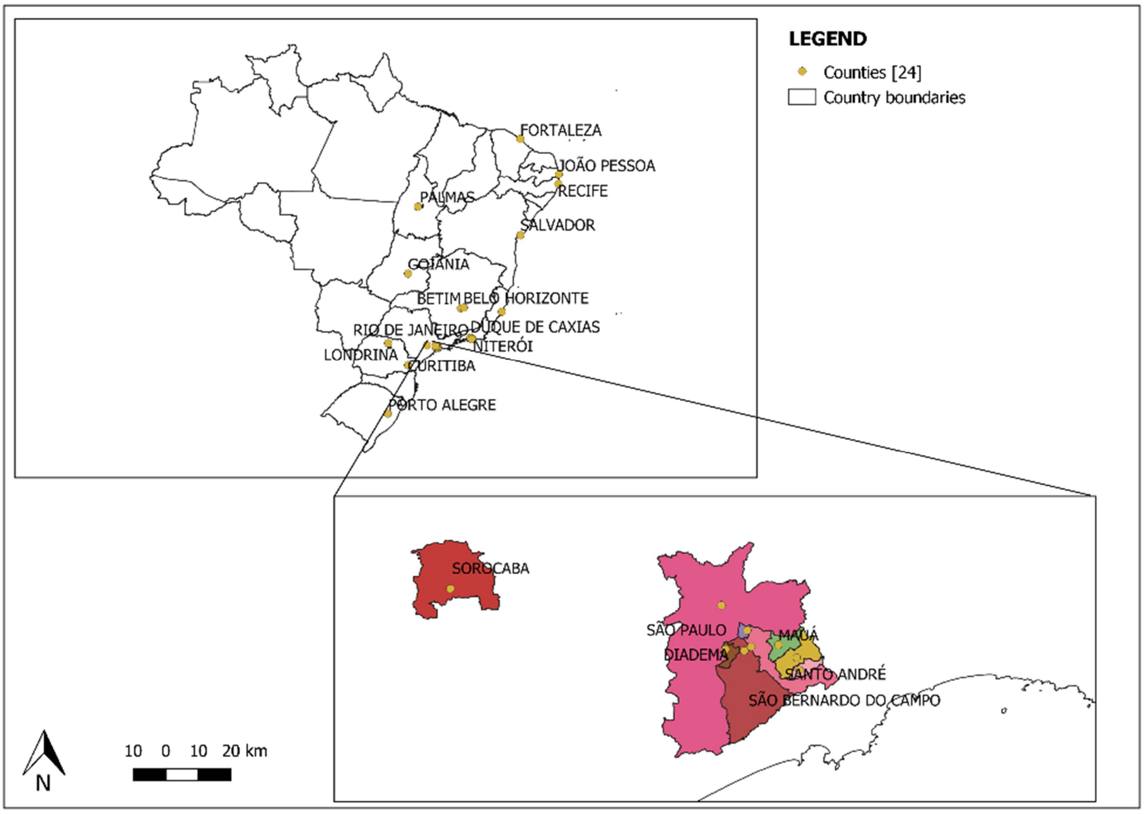

Figure 1 – Brazilian cities that developed the GHG inventory

Source: Developed by the authors

Figure 2 shows the GDP distribution by economic activity in each Brazilian city. There is a predominance of service activities, which vary between 52% and 88% of the GDP. Betim, Mauá and Diadema are the cities where industrial activities have higher GDP shares (48%, 38% and 34%, respectively). Agriculture and livestock are not relevant economic activities for any of the 24 cities.

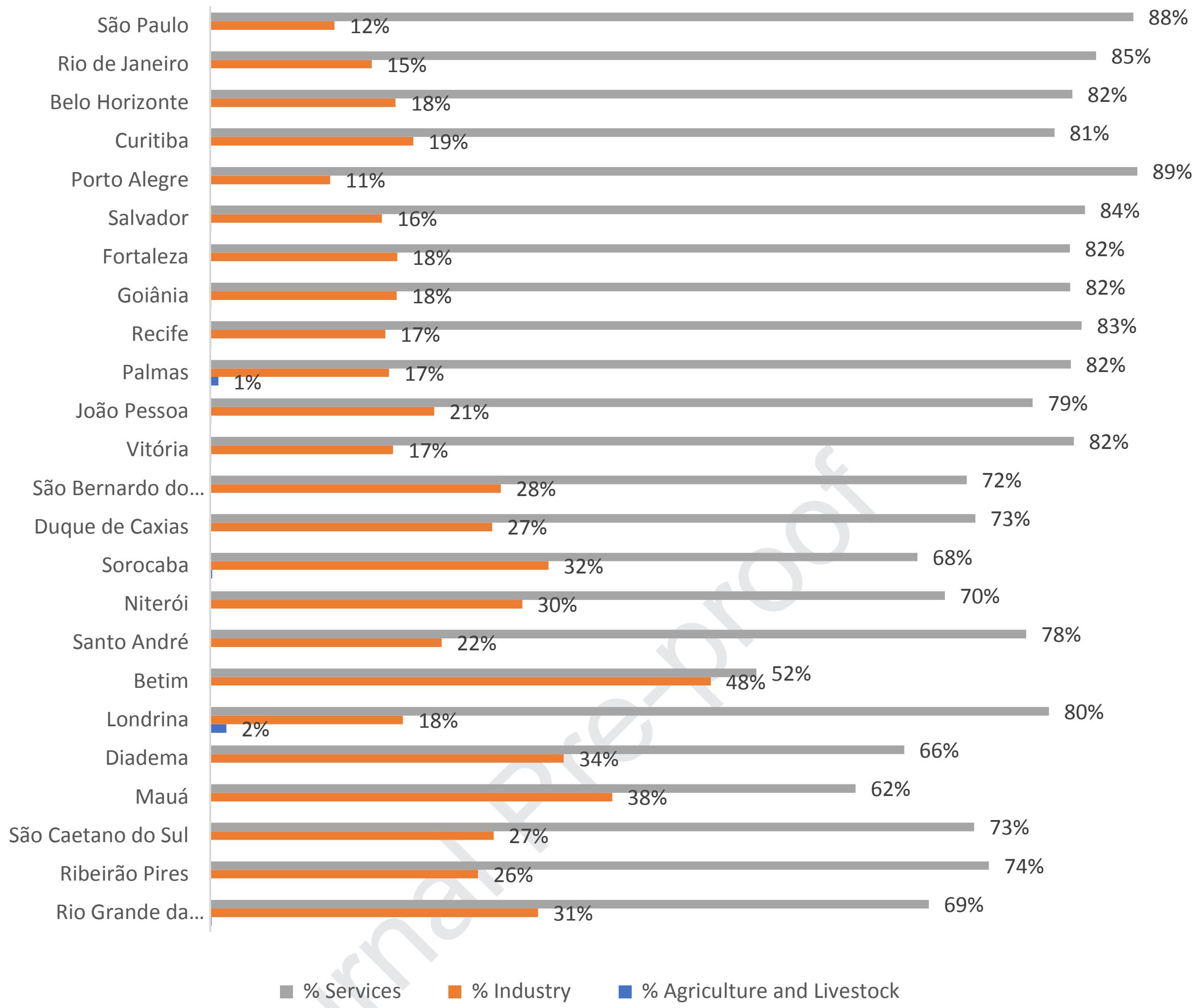

Figure 2 – GDP by Economic Activity (%)

Source: Developed by the authors from data of IBGE (2015)

Table 3 consolidates the accounting year, methodology used and GHG emissions results by scope according to GPC methodology of all cities. Nineteen cities used GPC methodology for their GHG inventories. Rio de Janeiro (Rio de Janeiro, 2015) and Goiânia (Goiânia, 2013) reported their GHG inventories using both GPC and IPCC methodologies.

Results of Belo Horizonte (Belo Horizonte, 2009), São Paulo (São Paulo, 2013) and Sorocaba (Sorocaba, 2014) followed IPCC, thus their emissions are not presented by scope. Londrina did not present their results by scope (Londrina, 2017), though its GHG inventories follow GPC. GHG Inventory Report for the ABC Region does not distribute emissions of each city per scope, just in the aggregate (Consórcio Intermunicipal do Grande ABC, 2017a).

Table 3: GHG Emissions by Scope Per City

City	Base Year	Methodology	Total Emissions (tCO_2e)	Emissions - Scope 1 (tCO_2e)	Emissions - Scope 2 (tCO_2e)	Emissions - Scope 3 (tCO_2e)
ABC Region	2014	GPC	**9.879.437**	8.451.956	1.227.278	200.202
Belo Horizonte	2007	IPCC	**3.187.983**			
Betim	2013	GPC	**2.250.980**	1.394.960	856.020	
Curitiba	2013	GPC	**4.125.853**	2.686.651	349.791	1.089.411
Duque de Caxias	2014	GPC	**2.264.578**	2.001.034	263.543	244.277
Fortaleza	2012	GPC	**3.827.521**	2.162.866	213.992	1.450.663
Goiânia	2012	GPC and IPCC 2006	**2.686.640**	1.890.800	125.520	670.320
João Pessoa	2014	GPC	**2.837.499**	2.309.846	194.421	333.232
Londrina	2013	GPC	**1.105.964**			
Niterói	2015	GPC	**1.729.602**	1.134.408	164.574	430.620
Palmas	2013	GPC	**646.478**	589.055	36.336	21.087
Porto Alegre	2013	GPC	**2.829.128**	1.917.235	350.704	561.189
Recife	2015	GPC	**3.120.426**	1.687.504	203.869,	1.229.053
Rio de Janeiro	2012	GPC and IPCC 2006	**22.637.140**	19.344.810	1.413.430	1.563.040
Salvador	2013	GPC	**3.698.963**	3.242.166	366.395	90.402
São Paulo	2009	IPCC 2006	**15.115.000**			
Sorocaba	2012	IPCC 2006	**1.108.205**			
Vitória	2015	GPC	**2.798.291**	2.424.305	367.109	6.877

Source: Developed by the authors using data of GHG reports of the cities

4.2 Emission analysis

Content analyses of GHG Reports were carried out and Figure 3 shows the relevance of the scopes for each city. Emissions from scope 1 are the most relevant to all Brazilian cities in this study. Scope 1 covers emissions in-boundary related to stationary energy, transport, waste, IPPU and AFOLU.

All cities reported electricity consumed from the National Interconnected System by industries, residences, commercial and institutional buildings, independently of whether electricity generation occurred in their boundaries. These emissions are reported as scope 2. Most of the cities also reported some indirect emissions, which were mainly emissions related to waste disposal out boundaries and transport (e.g., air travel and maritime freight).

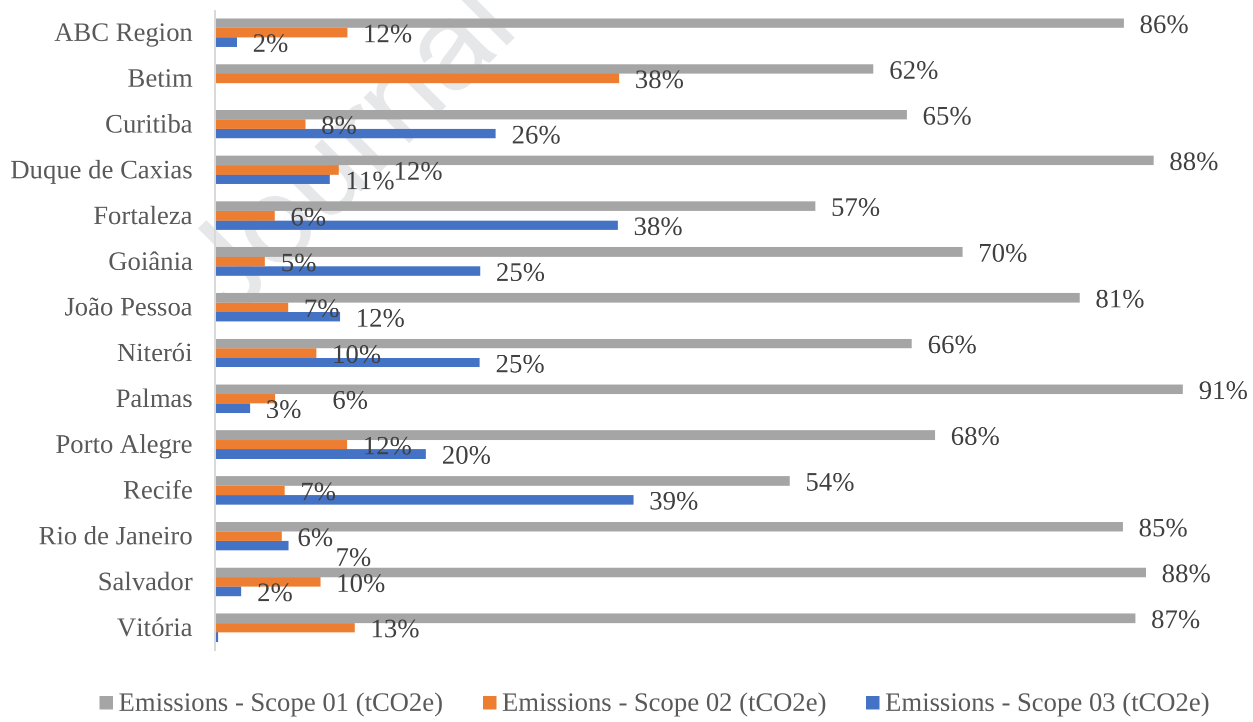

Figure 3 – GHG Emissions by Scope (%)

Source: Developed by the authors using data of GHG reports of the cities

Figure 4 shows GHG emissions by sector. All cities reported emissions related to (I) stationary energy, including electricity imported by the grid; (II) transport; and (III) waste. Sixteen cities reported only these three categories. Some did so because it was their first experience in conducting a GHG inventory (e.g., Recife, Fortaleza, ABC Region, Porto Alegre), while others (e.g., São Paulo) decided to focus on the main relevant emission sources, as suggested by the literature (Damsø et al., 2016; Li et al., 2017b)

Four cities reported IPPU (Duque de Caxias, Rio de Janeiro, São Paulo and Palmas), and seven cities (Duque de Caxias, Curitiba, Goiânia, Palmas, São Paulo, Sorocaba and Rio de Janeiro) reported AFOLU emissions/removals. Emissions related to consumption are just considered by Duque de Caxias (Duque de Caxias, 2016).

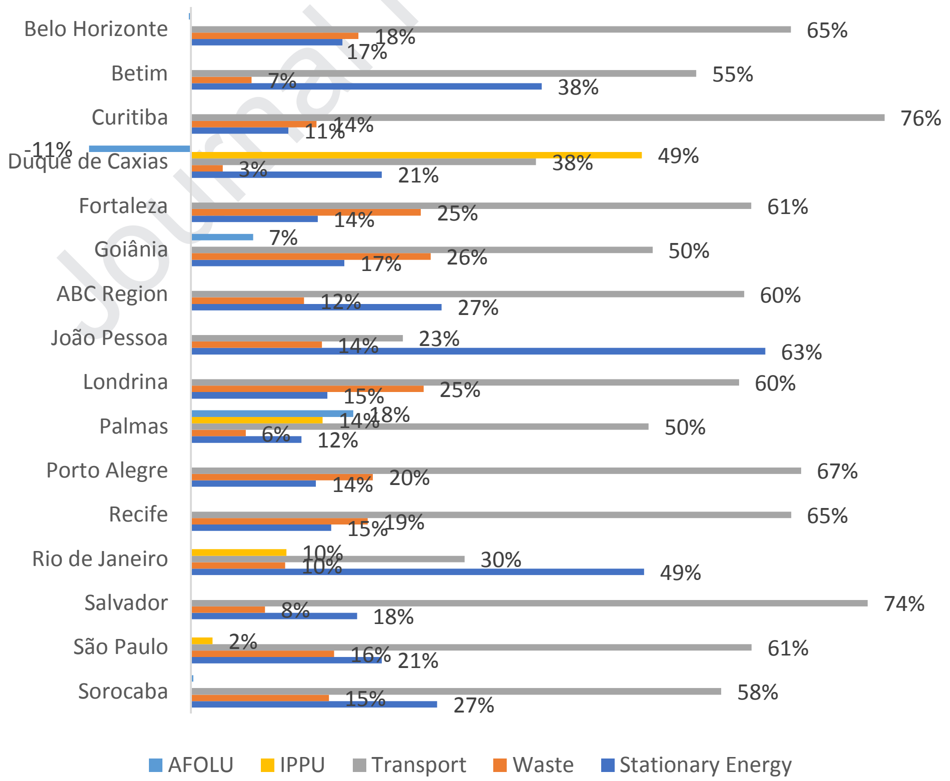

Figure 4 – GHG Emissions by Sector (%).

Source: Developed by the authors using data of GHG reports of the cities

As discussed in 4.2.2, transport is the most relevant GHG emission source. The only exceptions are Duque de Caixas, João Pessoa and Rio de Janeiro. When sub-sectors are analyzed, it can be seen differences between GHG emissions sources accounted by each city in the same sector, as detailed below.

4.2.1 Stationary Energy

Stationary energy includes emissions related to the generation of all energy sources for residential, commercial and institutional buildings; manufacturing industries and construction, energy industries and agriculture, forestry and fishing activities (WRI, 2014). There is a certain uniformity of stationary energy emission sources reported by Brazilian cities as showed by table 4.

Figure 5 shows stationary energy emissions for each city and its relevance for each city GHG inventory. Rio de Janeiro presents higher stationary energy emissions. These emissions are mainly related to energy consumption of three thermoelectric plants that generate electricity from fossil fuel (28%), industries (22%), residential buildings (16%) and commercial and institutional buildings (14%) (Rio de Janeiro, 2015).

São Paulo also shows relevant stationary emissions, mainly associated to (I) natural gas and liquified petroleum Gas (LPG) consumed by residential buildings (37%); (II) natural gas consumed by industries (23%) and (III) fuels used to generate electricity (20%) (São Paulo, 2013). Industries (65%) and residential buildings (21%) present the most relevant stationary emissions of the ABC Region. The most important fuels are Electricity (45%), LPG (13%) and Natural Gas (13%) (Consórcio Intermunicipal do Grande ABC, 2017a). João Pessoa presents important stationary emissions due to an oil power plant located in the city (72%) (João Pessoa, 2018) and

Betim (Betim, 2016) shows relevant stationary emissions related just to electricity consumption, as discussed in table 4.

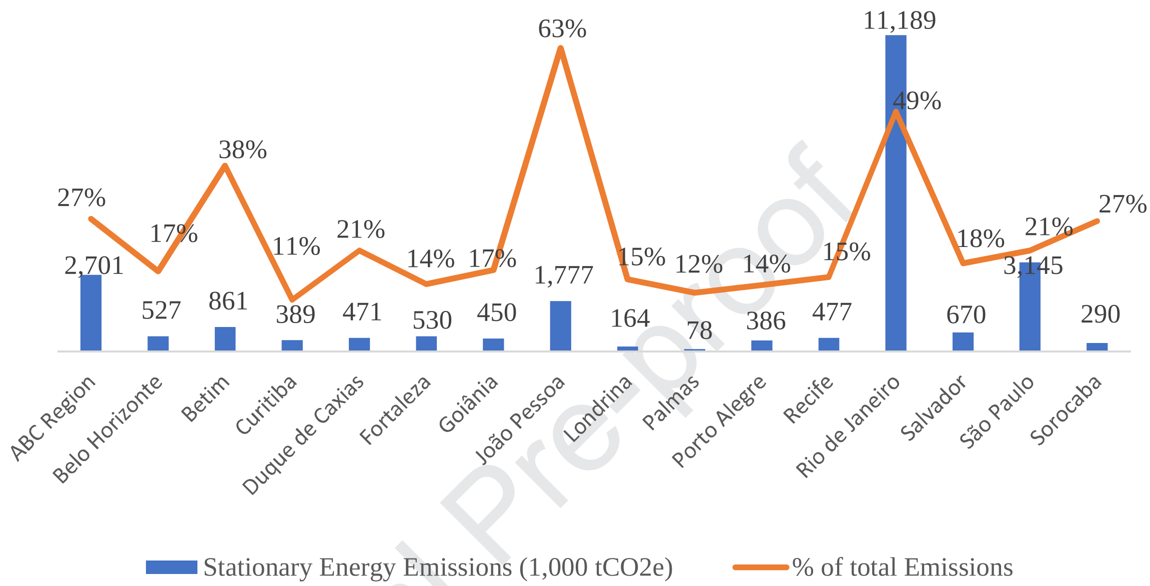

Figure 5 – Stationary Emissions by City (tCO2e).

Source: Developed by the authors using data of GHG reports of the cities

Emissions calculations were based on fuels sold inside the city to generate thermal energy and electricity consumed from the National Grid. When cities followed IPCC Guidelines (Belo Horizonte, 2009; São Paulo, 2013; Sorocaba, 2014; Rio de Janeiro, 2015; Duque de Caxias, 2016), Stationary and Transportation were considered in the same sub-sector. When GPC was followed, these emissions sources were accounted individually.

4.2.2 Transport

The transport sector included transportation by on-road, off-road, railway, aviation and waterborne navigation (WRI, 2014). When there was no airport or access to a sea/river, these emissions were not presented (e.g. ABC region Report). However, using a CBA approach, even for cities where there is no airport or port, emissions associated to air travel and maritime transportation of products consumed by its population should be accounted.

In general, these emissions were calculated considering fuels sold inside the cities' boundaries (e.g. Sorocaba, 2014; Recife, 2015; Curitiba, 2016; Consórcio Intermunicipal do Grande ABC, 2017a).

Emissions from transport are the most important GHG source for almost all cities. The only exceptions are (I) Duque de Caixas, where IPPU emissions are the most relevant (Duque de Caxias, 2016), (II) João Pessoa (João Pessoa, 2018) and (III) Rio de Janeiro (Rio de Janeiro,2015), where stationary emissions have the highest numbers. Figure 6 shows transport emissions and its relevance for each GHG inventory.

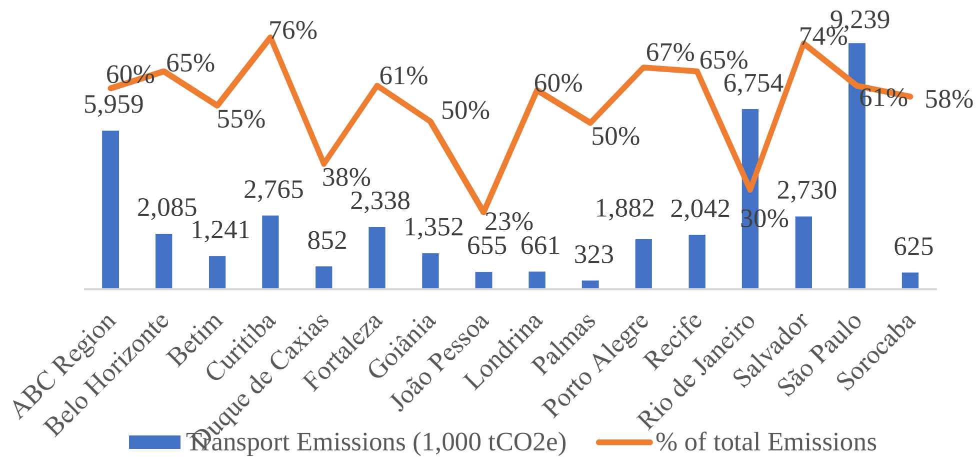

Figure 6 – Transport Emissions by City (tCO2e).

Source: Developed by the authors using data of GHG reports of the cities

São Paulo, Rio de Janeiro and ABC Region present the highest transport emissions numbers. São Paulo and Rio de Janeiro are the cities with highest population and vehicle fleet. Diesel consumed by trucks are the most important transport emission source in ABC Region (Consórcio Intermunicipal do Grande ABC, 2017a).

4.2.3 IPPU - Industrial Process and Product Use

São Paulo, Rio de Janeiro, Duque de Caxias and Palmas are the only cities that accounted IPPU emissions. In Duque de Caixas (Duque de Caxias, 2016), IPPU emissions are related to emissions from the Duque de Caxias Petroleum Refinery. Emissions from cement and steel production were also considered in this category, although production plants were not located in the city. This city also estimated emissions from using refrigerators, foams, aerosols and air conditioners.

In Rio de Janeiro (Rio de Janeiro, 2015), it was reported leakage emissions presented in glass, methanol and steel production. Emissions related to the use of lubricants and greases were also considered. São Paulo (São Paulo, 2013) also reported emissions leakage occurred due to glass production and lubricants and greases use in addition to the use of substances that cause ozone layer depletion. Palmas (Palmas, 2017) did not detail information about IPPU emissions sources measured. Figure 7 shows IPPU emissions by city.

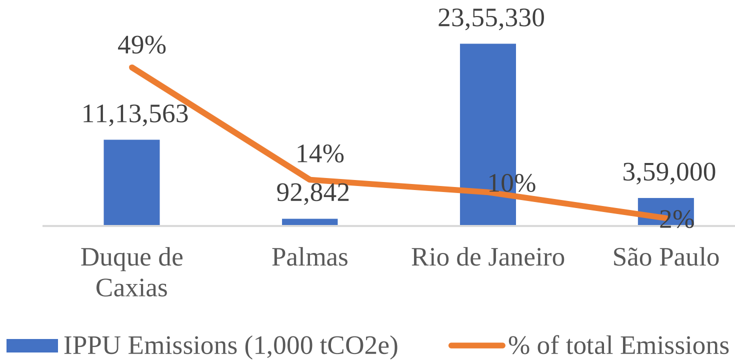

Figure 7 –IPPU Emissions by City (tCO2e).

Source: Developed by the authors using data of GHG reports of the cities

4.2.4 Waste

Waste emissions covered emissions associated with waste management, independent of whether these practices occurred in-boundary or out-boundary (WRI, 2014). All cities measured in-boundary waste emissions. Only three cities – Palmas (Palmas, 2017), Rio de Janeiro (Rio de Janeiro, 2011) and São Paulo (São Paulo, 2013) considered all practices of waste management. The main gap is the biological treatment of waste that was just considered by these cities. Incineration was either not always accounted, thus only nine cities reported, as discussed in table 4. As the largest cities in the group, Rio de Janeiro and São Paulo present the highest emissions from waste as shown in figure 8. Goiânia (Goiânia, 2013), Fortaleza (Fortaleza, 2016a) and Londrina (Londrina, 2017) are the cities where waste emissions are the most relevant.

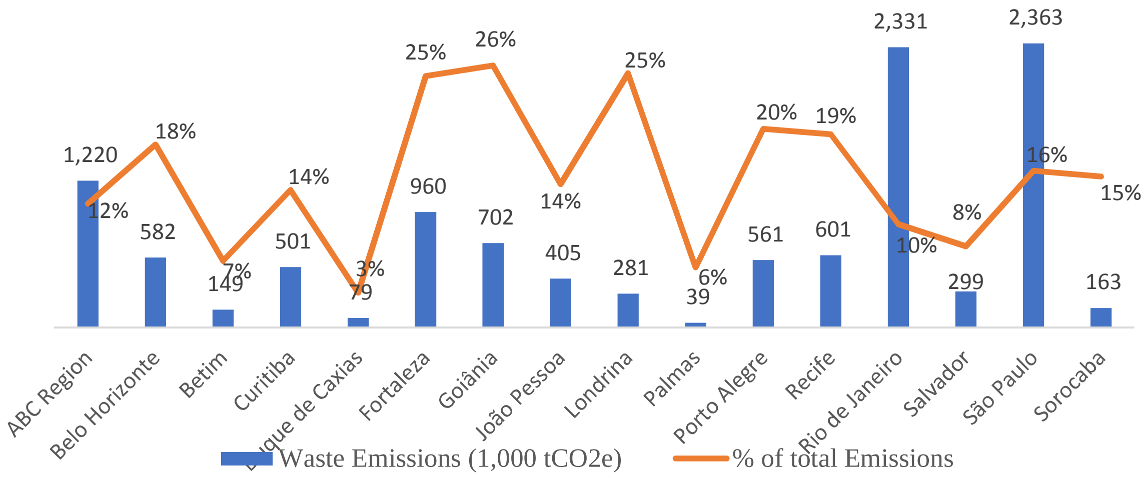

Figure 8 –Waste Emissions by City (tCO_2e).

Source: Developed by the authors using data of GHG reports of the cities

4.2.5 AFOLU - Agriculture, Forestry, and Other Land Use

AFOLU emissions and removals included agriculture, forestry and other land use. In Palmas (Palmas, 2017) and Goiania (Goiania, 2013), AFOLU showed some relevance due to urban pressures over green areas and livestock activities. In Duque de Caxias (Duque de Caxias, 2016), the carbon capture by green areas produced relevant carbon removals as presented in figure 9.

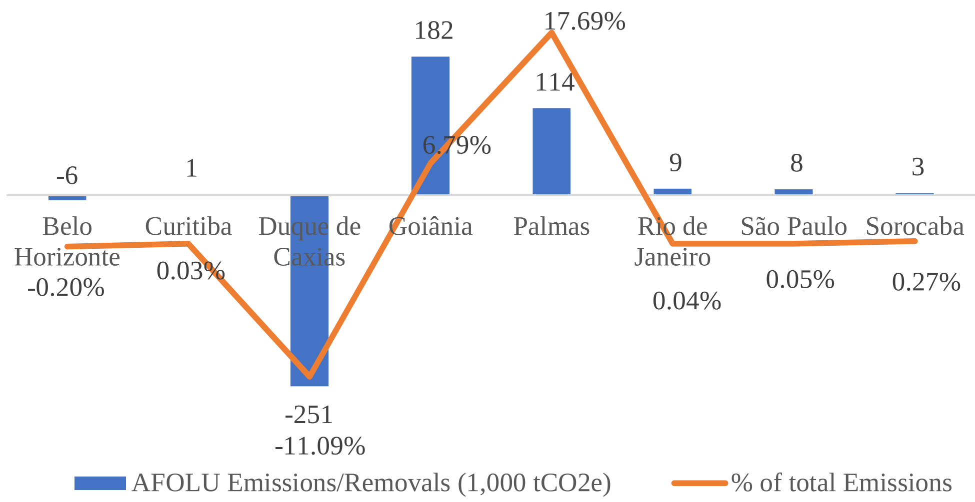

Figure 9 –AFOLU Emissions/Removals by City (tCO2e).

Source: Developed by the authors using data of GHG reports of the cities

4.3 Carbon Accounting Approaches

Brazilian cities are not using CBA approach to develop a GHG inventory. All cities used a PBA approach, adding emissions associated with (1) electricity consumed produced out-boundary; (2) waste emissions generated by the city but disposed at out-boundary sites; and in some cases (3) transport emissions that occurred out-boundary (e.g., air travel, maritime).

This practice is not found in the traditional PBA generally used by cities worldwide. Cities following the PBA usually do not consider these sources, as for example, when Harris et al. (2012) analyzed Hong Kong inventories and Andrade et al. (2018) examined Madrid's GHG emissions.

Brazilian cities did not account emissions associated with food, beverages and manufactured goods consumed by the city but produced out-boundary. The city of

Duque de Caxias (Duque de Caxias, 2016) was the only city to measure emissions from cement and steel that was used in the city.

The literature shows that an important share of a city emission can be attributed to the production and transport of imported products and services from outside the city's boundaries, such as food, manufactured products and consumables (Dodman, 2009; Lombardi et al., 2017; Andrade et al., 2018).

The experience of London using PAS 2070-DPSC showed that goods and services comprise an additional 18% of emissions, with food and drink being the major contributor (Greater London Authority, 2014). Andrade et al. (2018) showed that Madrid doubled their total GHG emissions under the PBA when using the PAS 2070-DPSC Standard.

Emissions from the production and transport of imported products and services can be particularly relevant for the Brazilian cities in this study once their economies are mainly based on services. This implies that food, beverages, construction inputs and other manufactured products consumed by the population within the boundaries of those cities are produced elsewhere. Emissions associated with these products have not been accounted by these Brazilian cities.

The Brazilian official statistics institutions do not provide information regarding products bought or sold from other cities/states in Brazil. There is no environmentally extended input output (or EEIO) for Brazilian cities. This fact makes it difficult to develop a CBA inventory. More complex calculations and assumptions would be needed, increasing uncertainties. These findings were highlighted as a disadvantage by several authors (Peters, 2008; Dodman, 2009; Grasso, 2016; Afionis et al., 2017; Franzen & Mader, 2018; Sudmant et al., 2018).

Data obtained from Research of Families Budget developed by IBGE (2009) shows that food, clothing and personal care consumed by urban population represent from 8.4% to 19.4% of the cities' GDP. Among these items, expenditures related to food have the greatest importance in all cities. As these cities do not present relevant agriculture and industrial activities, it is reasonable to assume that these items come from another city, state or country. Therefore, emissions related to their production were not accounted in the inventories of the cities.

Although a CBA approach would provide more comprehensive results and a more complete diagnosis of city emissions, many estimates would have to be developed, which could hinder the accuracy of the results. This is aligned with the CBA disadvantages mentioned in the literature (Peters, 2008; Dodman, 2009; Grasso, 2016; Afionis et al., 2017; Franzen & Mader, 2018; Sudmant et al., 2018).

GHG inventories of Brazilian cities have considered some sources of indirect emissions, but there is still a long way to go to achieve the complete application of methods such as the PAS 2070-DPSC. For this application to be possible, it is necessary to improve statistical information at the city level, which is recommended by Andrade et al. (2018).

4.4 Differences and Gaps in the GHG inventories

The gaps identified in Brazilian cities GHG reports can be divided into two main types: incompleteness a lack of transparency.

Gap 1 – Incompleteness: The reported GHG emissions shall appropriately reflect emissions occurring as a result of activities and consumption patterns of the city (WRI, 2014). Cities shall account for all required emissions sources within the inventory boundary. Some GHG inventories did not account GHG emissions of all economic sectors and emissions sources, independently of the carbon accounting approach chosen. For example, in the report of Betim (Betim, 2016), where industrial sector is the most important economic activity, no source of stationary energy neither IPPU were accounted. The report of ABC region (Consórcio Intermunicipal do Grande ABC, 2017a), where more than 2.7 million people live, no emission related to aviation was considered because there is no airport at the region. At these GHG emissions inventories, relevant emission sources may be neglected. Therefore, GHG results can be underestimated. Consequently, results can guide limited actions to combat climate change within the city.

Gap 2 - Lack of Transparency: Data, emission sources, emission factors, and accounting methodologies require adequate documentation and disclosure to enable verification. The information should be enough to allow individuals outside of the inventory process to use the same source data and derive the same results. All exclusions shall be clearly identified, disclosed and justified. Several GHG inventories were not transparent. Some reports did not present input data, emission sources included; emission factors or calculation methodologies (e.g. Betim, Recife, Fortaleza, Porto Alegre, Salvador, São Paulo). The lack of transparency of these GHG inventories limits the reproducibility of their results by a third party . Therefore, it is not feasible to assess the accuracy of the GHG results of these reports.

Both gaps are indirectly mentioned in previous literature. Croci et al. (2017), analyzing mitigation options of 124 European cities, found that GHG inventories of these cities did not cover the same sectors. Mia et al. (2019), analyzing GHG disclosure of 42 mega cities from C-40, also found that GHG inventories were incomplete, once they did not account for all emission sources and GHG, and they present deficiencies regarding transparency.

Seventeen GHG reports presented incompleteness (Gap 1) and twenty presented lack of transparency (Gap 2). Table 4 presents details of each report and a discussion about sectors and sub-sectors considered by each city, highlighting gaps and limitations of each report.

In order to close the gaps identified in the research and seeking to contribute to the efforts, asked by Mi et al. (2019), of reducing uncertainties of cities emission inventories, several initiatives could be easily executed, such as identification of the main economic activities and consumption patterns that could generate large emissions and the presentation of source of inputs. Table 5 summarizes the potential actions to reduce the emissions.

Table 4 – Sectors, Sub-sectors and Gaps of Each Report

City	Sectors and Emission Sources Included in GHG Inventories					Gaps		Discussion about subsectors, gaps and limitations
	Stationary Energy	Waste	Transport	IPPU	AFOLU	1	2	
ABC Region	Residential Buildings Commercial and Institutional Buildings Manufacturing Industries and Construction	Solid waste disposal (SWD) Incineration and open burning of waste Wastewater treatment	On Road Off-Road Railways	N.A.[3]	N.A.	Yes	Yes	GHG Report is transparent about assumptions, emission factors and some limitations of the report. However, input data used for calculation is not presented. GHG results cannot be reproduced. The following sub-sectors were not accounted: • Aviation and Waterborne navigation; • Biological treatment of waste; • One incineration site was not considered due to lack of data; • IPPU and AFOLU emissions.
Belo Horizonte	Residential Buildings Commercial and Institutional Buildings	SWD Wastewater treatment	On Road Aviation	N.A.	Land Use	No	No	GHG Report is transparent about emissions sources, calculation methodologies and limitations. However, it does not present input data used. The following sub-sectors were

[3] N.A. means Not accounted.

City	Sectors and Emission Sources Included in GHG Inventories					Gaps		Discussion about subsectors, gaps and limitations
	Stationary Energy	Waste	Transport	IPPU	AFOLU	1	2	
	Manufacturing Industries and Construction Fugitive Emissions from Oil and Natural Gas System							not accounted: • Waterborne navigation, Railway and Off-Road transportation are not mentioned; • Incineration and Open Burning and Biological treatment; • IPPU; • Livestock.
Betim	Residential Buildings Commercial and Institutional Buildings Manufacturing Industries and Construction Energy Industries Non-Specified Sources	SWD Wastewater treatment	On Road Railways Aviation	N.A.	N.A.	Yes	Yes	GHG Report is not transparent about assumptions, input data, emission factors and limitations. It was identified that GHG results may be underestimated because: • It was considered just electricity in Stationary Energy. Betim has relevant industrial sector and no other stationary energy emission was accounted. This emission source could be relevant once industrial activities represent 48% of the city GDP.

City	Sectors and Emission Sources Included in GHG Inventories					Gaps		Discussion about subsectors, gaps and limitations
	Stationary Energy	Waste	Transport	IPPU	AFOLU	1	2	
								• Waterborne navigation and Off-Road transportation were not accounted; • IPPU, AFOLU and Open Burning and Biological treatment of waste were not considered.
Curitiba	Residential Buildings Commercial and Institutional Buildings Manufacturing Industries and Construction Energy Industries Agriculture, forestry and fishing activities	SWD Wastewater treatment	On Road Off-Road Waterborne Navigation Railways Aviation	N.A.	AFOLU	No	Yes	GHG Report is not transparent about assumptions, input data, emission factors and limitations. Fugitive emissions of HFCs are mentioned but not accounted. Biological treatment of waste was not considered in Waste sub-sector. GHG Report presents result for AFOLU but do not provide additional information about sub-sectores measured.

City	Sectors and Emission Sources Included in GHG Inventories					Gaps		Discussion about subsectors, gaps and limitations
	Stationary Energy	**Waste**	**Transport**	**IPPU**	**AFOLU**	**1**	**2**	
Duque de Caxias	Residential Buildings Commercial and Institutional Buildings Manufacturing Industries and Construction Energy Industries	SWD Wastewater treatment	On Road Off-Road Waterborne Navigation Railways Aviation	Industrial Processes (IP) Product Use (PU)	Livestock Land Use and Wood Consumption	No	No	GHG Report is transparent about assumptions, input data, sources of data and emission calculation. One of the most complete GHG inventory among Brazilian cities. Incineration and Open Burning and Biological treatment of waste were not considered.
Fortaleza	Residential Buildings Commercial and Institutional Buildings Manufacturing Industries and Construction Energy Industries	SWD Incineration and open burning of waste	On Road Off Road Aviation	N.A.	N.A.	Yes	Yes	GHG Report is not transparent about assumptions, input data, emission factors and limitations. The following sub-sector were not accounted: • Railway; • Biological treatment of waste and wastewater treatment; • IPPU and AFOLU.
Goiânia	Residential Buildings Commercial and	SWD Wastewater treatment	On Road Off Road Aviation	N.A.	Livestock Land Use	Yes	Yes	GHG Report is not transparent about assumptions, input data and emission factors. Report did not consider:

City	Sectors and Emission Sources Included in GHG Inventories					Gaps		Discussion about subsectors, gaps and limitations
	Stationary Energy	Waste	Transport	IPPU	AFOLU	1	2	
	Institutional Buildings Manufacturing Industries and Construction Energy Industries							• Railway and Waterborne Navigation; • Biological treatment and Incineration; • IPPU.
João Pessoa	Residential Buildings Commercial and Institutional Buildings Manufacturing Industries and Construction Energy Industries Non-Specified Sources	SWD Incineration and open burning of waste Wastewater treatment	On Road Off-Road Railways Aviation	N.A.	N.A.	Yes	Yes	GHG Report is transparent about assumptions and emission factors but input data are not presented. Waterborne navigation was not considered due to lack of data. IPPU and AFOLU were not accounted.
Londrina	Residential Buildings Commercial and Institutional Buildings	SWD Incineration and open burning of waste	On Road Off-Road Aviation	N.A.	N.A.	Yes	Yes	GHG Report is transparent about assumptions and input data. However, emission factors and calculation methods are not presented. GHG Report did not account:

City	Sectors and Emission Sources Included in GHG Inventories					Gaps		Discussion about subsectors, gaps and limitations
	Stationary Energy	Waste	Transport	IPPU	AFOLU	1	2	
	Manufacturing Industries and Construction Energy Industries Agriculture, forestry and fishing activities Non-Specified Sources	Wastewater treatment						• Railway and Waterborne; • Biological treatment of waste; • IPPU and AFOLU.
Palmas	Residential Buildings Commercial and Institutional Buildings Manufacturing Industries and Construction	SWD Incineration and open burning of waste Biological treatmente of waste Wastewater treatment	On Road Off-Road Waterborne Navigation Railways Aviation	IP PU	Livestock Land Use	No	Yes	Authors have access just to main results of the GHG inventory. It was not possible to assess transparency of the report because the official report is not public.
Porto Alegre	Residential Buildings Commercial	SWD Wastewater treatment	On Road Railways	N.A.	N.A.	Yes	Yes	GHG Report is not transparent about input data and emission factors. GHG report did not account the following

City	Sectors and Emission Sources Included in GHG Inventories					Gaps		Discussion about subsectors, gaps and limitations
	Stationary Energy	Waste	Transport	IPPU	AFOLU	1	2	
	and Institutional Buildings Manufacturing Industries and Construction Energy Industries Agriculture, forestry and fishing activities		Aviation					sub-sectors: • Waterborne navigation; • Incineration and biological; • IPPU and AFOLU.
Recife	Residential Buildings Commercial and Institutional Buildings Manufacturing Industries and Construction	SWD Incineration and open burning of waste	On Road Waterborne Navigation Railways Aviation	N.A.	N.A.	Yes	Yes	GHG Report is transparent about assumptions and input data. However, it does not present emission factors. GHG Report did not present: • Biological treatment and wastewater treatment and discharge; • IPPU; • AFOLU.

City	Sectors and Emission Sources Included in GHG Inventories					Gaps		Discussion about subsectors, gaps and limitations
	Stationary Energy	Waste	Transport	IPPU	AFOLU	1	2	
Rio de Janeiro	Residential Buildings Commercial and Institutional Buildings Manufacturing Industries and Construction Energy Industries Fugitive Emissions from Oil and Natural Gas System Agriculture, Forestry and Fishing Activities	SWD Incineration and open burning of waste Wastewater treatment Biological treatmente of waste in the city	On Road Off-Road Waterborne Navigation Railways Aviation	IP PU	Livestock Land Use Agriculture	No	Yes	GHG Report is not transparent about assumptions, input data and emission factors. It is one of the most complete GHG inventories among Brazilian cities. Energy sector includes Stationary Energy and Transportation.
Salvador	Residential Buildings Commercial and Institutional Buildings	SWD Incineration and open burning of waste Wastewater	On Road Waterborne Navigation Aviation	N.A.	N.A.	Yes	Yes	GHG Report is transparent about assumptions and sources of data. However, it does not present input data and emission factors. Biological treatment of waste, IPPU and

City	Sectors and Emission Sources Included in GHG Inventories					Gaps		Discussion about subsectors, gaps and limitations
	Stationary Energy	Waste	Transport	IPPU	AFOLU	1	2	
	Manufacturing Industries and Construction Energy Industries Agriculture, forestry and fishing activities	treatment						AFOLU were not accounted.
São Paulo	Residential Buildings Commercial and Institutional Buildings Manufacturing Industries and Construction Energy Industries Fugitive Emissions from Oil and Natural Gas System Non-Specified	SWD Incineration and open burning of waste Wastewater treatment Biological treatmente of waste in the city	On Road Off Road Waterborne Navigation Aviation	IP PU	Livestock Land Use Agriculture	No	Yes	GHG Report is not transparent about assumptions, input data and emission factors used for calculation. It does not present Gap 1.

City	Sectors and Emission Sources Included in GHG Inventories					Gaps		Discussion about subsectors, gaps and limitations
	Stationary Energy	Waste	Transport	IPPU	AFOLU	1	2	
	Sources							
Sorocaba	Residential Buildings Commercial and Institutional Buildings Manufacturing Industries and Construction	SWD Wastewater treatment	On Road Off Road Aviation	N.A.	Livestock Land Use Agriculture	Yes	No	GHG Report is transparent about assumptions, input data and emission factors used for calculation. IPPU; incineration and open burning and biological treatment were not considered.
Niterói and Vitória	Authors have access just to answers provided by these cities to CDP (CDP, 2019). GHG Reports are not publicly available. It was just possible to identify emission by sources							

Source: Developed by the authors with data of Cities' GHG Inventory Reports

Table 5 – Actions to overcome the Gaps

Gap 1: Incompleteness	Gap 2: Lack of transparency
• To identify main economic activities and consumption patterns of the city; • To identify emission sources considering both approaches PBA and CBA; • To assess the necessary data to emission calculation; • To analyze the feasibility of data collection; • To decide about carbon accounting approach, boundaries sectors and subsectors to be measured; • To use more robust information system that allow an integrated production-consumption approach.	• To identify clearly boundaries, sectors and sub-sectors included in the GHG inventory; • To justify any exclusion; • To present clearly assumptions, input data, source of input data, calculation methodologies and emission factors used for GHG emission calculation; • To describe limitations and uncertainties of the report; • To engage stakeholders on GHG inventory development with a more transparent and participatory process.

Source: Developed by the authors

4.5 Impacts on Climate Action Plans

Belo Horizonte (Belo Horizonte, 2013), Fortaleza (Fortaleza, 2016b), Recife (Recife, 2016), Rio de Janeiro (Rio de Janeiro, 2015) and the ABC region (Consórcio Intermunicipal do Grande ABC, 2017b) have climate action plans approved by the local city councils. The climate action plan of the ABC region was developed with integrated actions for all 7 cities. Other cities that developed GHG inventories are also planning actions to reduce GHG emissions (Carbonn, 2019). However, a structured climate action plan was not approved by local councils yet.

Climate action plans of these cities follow a similar structure. They consider activities in the transport, energy and waste sectors. Fortaleza (Fortaleza, 2016b) and Recife (Recife, 2016) consider a fourth sector that includes actions related to urban development. Belo Horizonte (Belo Horizonte, 2013) also considered actions on sanitation and adaptation to climate change.

In the transport sector, several actions are planned in the climate action plans: improvement of public transport with new equipment (BRTs, VLTs, Metro Lines); infrastructure for bicycles and pedestrians; increase of biofuels in the public fleet and bike and car sharing. For the energy sector, actions on public lighting and building efficiency as well as solar energy use, and incentives for renewable energy have been proposed. Regarding the waste sector, cities seek to reduce waste disposal at landfills. They also plan to implement electricity generation from biogas and increase recycling and composting practices. The sector of urban development considered adaptation actions and activities to promote green areas (e.g., conservation, afforestation and reforestation) and green building. In Belo Horizonte, regarding adaptation the plan intends to: (I) review local rainwater management law; (II) define targets for implantation of permeable and light color floors; (III) improve the monitoring and alert network of extreme weather; and (IV) to establish partnerships to protect and to increase urban vegetation. For sanitation, the plan aims to provide 100% of the population with wastewater treatment and using biogas from wastewater treatment station.

The fact that no city used a CBA approach have an impact on their climate action plans. Reflecting their inventories, no climate action plan considered mitigation actions regarding consumption of goods and manufactured products that were produced out-boundary. Therefore, the climate impact of imported carbon emissions is not considered. This may limit the effectiveness of established local climate policies (Peters, 2008; Harris et al., 2012; Vetné Mózner, 2013; Grasso, 2017; Afionis et al., 2017; Andrade et al. 2018), and an opportunity to engage and encourage more sustainable consumption habits in the local community is lost.

5. Conclusions

Several authors (e.g. Dodman, 2009; Harris et al., 2012; Lombardi et al., 2017; Sudmant et al., 2018; Andrade et al., 2018) discuss the impact of the carbon accounting approach on urban GHG emissions inventories and some recent papers propose methods to improve the comprehensiveness and accuracy of carbon accounting for cities. Through a critical analysis of the literature, this study summarized benefits and disadvantages of using each carbon accounting approach. Although several authors support the adoption of the CBA approach, the disadvantages of this approach are also highlighted by several studies, such as the lack of data available at the local level impacting the accuracy of the results (Peters, 2008; Afionis et al., 2017; Franzen & Mader, 2018).

The research verified that PBA is used by Brazilian cities with the aggregation of indirect emissions of electricity, waste disposed in out-boundary landfills, and emissions from aviation (with few exceptions). Most the cities uses GPC methodology. Five cities use IPCC. Brazilian cities have not accounted for GHG emissions from food, beverages and manufactured products that are consumed by cities and produced out-boundary. Thus, the emissions from all cities may be underestimated in agreement with previous literature (Dodman, 2009; Lombardi et al., 2017; Andrade et al., 2018).

Literature focusing on the quality of these reports are rare (Mia et al., 2019). Two main gaps were identified in Brazilian cities GHG emissions reports: incompleteness and lack of transparency.

Seventeen Brazilian cities presented major incompleteness gap. These cities do not account important sectors and sub-sectors in their GHG reports. Relevant emission sources in some cities, such as stationary energy, may be neglected. Therefore, GHG results can be underestimated.

Twenty GHG reports presented lack of transparency. At these reports, there are no transparency about assumptions, input data, source of input data, emission factors, calculation methods and limitations. Without these types of information, it is difficult to verify the accuracy of the report and make it difficult to replicate the study in future inventories, as well as to make comparisons among cities and changes in carbon emissions over time, which is important for benchmarking and analysis of the effectiveness of actions to mitigate climate change.

The carbon accounting approach chosen, and the gaps identified in our study impact the quality of GHG inventories, and consequently climate mitigation plans do not consider actions to promote sustainable consumption and to change consumption patterns of the population.

In order to overcome these gaps, there are some actions that can improve the quality of the GHG inventories. Using robust information system that allow an integrated production-consumption approach would be a possible solution to help cities to overcome incompleteness gap. Also, developing the GHG inventory with more stakeholder engagement and disclosing clearly boundaries, assumptions, input data, emission sources included, exclusions and limitation would eliminate the lack of transparency gap.

As few Brazilian cities have developed emission inventories and even fewer cities have enacted low-carbon plans as laws, for policy makers there is an opportunity to motivate the development of broader and more complete GHG inventories that may lead to low-carbon plans that involve and make the population aware of the importance of their consumption choices in relation to the climate.

This paper has several contributions to fill the gaps in the scientific literature and provides insights for policy makers. Firstly, this manuscript contributes to the literature in comparing the different GHG methodologies for cities in terms of coverage, efforts and usage. Secondly, there is lack of empirical research that investigates the quality of GHG disclosures at city level as pointed by Mia et al. (2019). By assessing GHG inventories of Brazilian cities, this study identified the main gaps of city emissions inventories. Efforts are necessary to reduce uncertainties of GHG inventories result (Mi et al., 2019) and this manuscript contributes to these efforts.

Thirdly, it provides a detailed study of inventories in a developing country. As Castán Broto & Bulkeley (2012) and Van der Heijden (2019) argue, the literature about city responses to climate change is dominated by economically developed countries. Despite the limitations of the method, this is one of the most complete studies in Latin America.

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[4] The following steps are necessary to find data used by the paper. (I) Access table 1594; (II) Check the following options: “Despesa monetária e não monetária média mensal familiar (Reais); “Total”; “1.Despesa Total”; “2. Despesas Correntes”; “2.1.1Alimentação”; “2.1.2. Habitação”; “2.1.3.Vestuário”; “2.1.4. Transporte”; “2.1.5. Higiene e cuidados pessoais”; “2.1.6. Assistência à saude”; “2.1.7. Educação”; “2.1.8. Recreação e cultura”; “2.1.9. Fumo”; “2.1.10. Serviços pessoais”; “2.1.11. Despesas diversas”; “2.2. Outras despesas correntes”; “Município”. After that, click on “Download” and information about family’s budget expenses for all Brazilian cities will be provided. Cities that are scope of our study must be selected.

[5] The following steps are necessary to find data used by the paper. (I) Access https://sidra.ibge.gov.br/tabela/5938 . After that, check the following options: “Produto Interno Bruto a preços correntes (Mil Reais)”; “Impostos, líquidos de subsídios, sobre produtos a preços correntes (Mil Reais)”; “Valor adicionado bruto a preços correntes total (Mil Reais)”; “Valor adicionado bruto a preços correntes da agropecuária (Mil Reais)”; “Participação do valor adicionado bruto a preços correntes da agropecuária no valor adicionado bruto a preços correntes total (%)”; “Valor adicionado bruto a preços correntes da indústria (Mil Reais)”; “Participação do valor adicionado bruto a preços correntes da indústria no valor adicionado bruto a preços correntes total (%)”; “Valor adicionado bruto a preços correntes dos serviços, exclusive administração, defesa, educação e saúde públicas e seguridade social (Mil Reais)”;

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HIGHLIGHTS

- Greenhouse gas inventories of Brazilian cities present two main gaps: incompleteness and lack of transparency. Emissions may be underestimated.
- Brazilian cities carbon emissions inventories are using Production-Based Approach adding indirect emissions of electricity, waste disposal in out-boundary landfills and aviation. The most part of the cities uses the methodology “Global Protocol for Community-Scale Greenhouse Gas Emission Inventories”.
- In order to overcome gaps identified in the research, some initiatives that can improve the quality of the Greenhouse Gas inventories are recommended.
- Greenhouse gas inventories of the cities that do not consider emission related to products consumed by cities and produced out-boundary promote carbon plans that do not consider initiatives for sustainable consumption.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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