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Estimating Greenhouse Gas Footprints of Sectors for the Brazilian Economy 1995-2009

by

João Murilo Silva Merico
jo6768si-s@student.lu.se

Abstract

The estimation of a country's greenhouse gas emissions has appropriately calculated the total footprint of a nation. However, when such estimates are brought down to the level of each economic activity, they do not reflect the total consumption pattern of a sector by not taking intersectoral relationships into account. Therefore, this study has two major purposes: (1) to estimate the greenhouse gas footprint of sectors in Brazil for the period 1995-2009; and (2) to propose a quantification of the emissions embodied in the national intersectoral relations during the same period. The empirical part of this study employed a Single-Region Input-Output (IO) table for Brazil obtained from the World Input-Output Database (WIOD). The results provide a novel contribution by accounting, for the first time, the footprint of Brazilian sectors and by proposing the classification of economic activities as net producers or net consumers of emissions, which arises from the quantification of intersectoral relations. The results unveil a different pattern of sectoral responsibility for pollution in Brazil.

Key words: Footprint; Sectors; Input-Output analysis; Greenhouse gas emissions.

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João Murilo
Lund University
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Table of Contents

List of Tables

List of Figures

1 Introduction

There are two main approaches to estimate a country's total emissions, a production-based account (PBA), which considers the emissions produced within a territory by its resident institutional units (Peters & Hertwich, 2008), or a consumption-based account (CBA, and also referred to as national emissions footprint) where emissions are estimated by excluding export related pollution and including emissions embedded in imports (Kander et al., 2015; Peters & Hertwich, 2008). The underlying reasons to estimate a nation's emissions based on its consumption rests on arguments that it creates a fairer assessment of emissions responsibility by placing some of the burden of its generation to the parties who benefited from its consumption (Davis & Caldeira, 2010). Another argument lies in that PBA does not consider the direct connections between economies, such as international trade, which may result in distorted analyses of the driving forces of emission trends, thus hampering mitigation strategies and policies (Peters et al., 2011).

Emissions footprint can be defined as the total, direct and indirect, greenhouse gas (GHG) emissions that are required to satisfy a given consumption (Minx et al., 2009). The method described above through which Davis and Caldeira (2010), Kander et al. (2015) and others have estimated CBA emissions can be considered a national footprint, because by subtracting exports, the domestically produced pollution is also consumed domestically (Peters & Hertwich, 2008). However, the same methodology has been applied when designating the contribution of sectors into the total national CBA accounts. In this way, sectors reflected the exact same equation used nationally, that is, the emissions represented a sector's domestic production, which is consumed domestically, plus imports, minus exports (e.g. Kander et al., 2015). The issue with this is that, at the sectoral level, the emissions it produced, although consumed domestically, were not necessarily consumed by the same activity. Only imports have been considered to calculate a sector's consumption. Therefore, despite national CBA estimates representing a country's footprint, its disaggregated values by economic activity do not reflect a sector's total consumption, and thus footprint.

At the same time, Kander et al. (2015) puts forward that any useful and reliable national emissions scheme for policy formulation must satisfy three conditions, they are: sensitivity, which means that emissions indicators need to be responsive to factors that a country can influence – such as the composition of their consumption –; monotonicity, where a national reduction in emissions cannot be done in such ways that lead to an increase in global emissions; and additivity, where the sum of all national emissions need to equal total global emissions (Kander et al., 2015). The estimation of national greenhouse gases under a CBA accounting system describes the emissions embodied in the aggregate consumption of a nation, but it does not take into account the consumption undertaken by sectors individually. This, on its turn, leaves out estimations of the interrelationships of economic activities by not accounting for the demand and production dependencies between domestic activities (Wiedmann et al., 2006). Therefore, a significant improvement to estimators in reflecting factors that a country can influence (i.e. sensitivity), and not leading to unintended increase in emissions (i.e. monotonicity) due to poor understanding of intersectoral dependency, can be achieved through quantifying the footprint of sectors, identifying sectoral GHGs hotspots and defining priority areas for emissions mitigation policies (Minx et al., 2009).

This on its turn, has profound impacts on environmental policy formulation. Proponents of an Environmental Kuznets Curve (EKC) argue that the level of pollution that arises from economic activity follows an inverted-U function of income and depends on the stage of development a country finds itself in (Kaika & Zervas, 2013; Dinda, 2004). Thus, an industrial-based economy would be heavily degrading the environment, but as income rises, a service-led economy would reduce its pollution levels to the point the environment begins to improve (Dinda, 2004). A transition to a service economy has been proposed as one of the main strategies to reduce human imprint on Earth, whilst pursuing continued economic growth (Pacala & Socolow, 2004). However, sectors tend to not exist in isolation from other activities, where services show a particular dependency on other sectors through demanding production across the economic structure (Parrique et al., 2019; Alcántara & Padilla, 2009; Suh, 2006). Therefore, the extent to which a service transition may indeed reduce the environmental impact of economic activity needs to take inter-sectoral relations into account.

Therefore, the purpose of this work is to contribute to the national footprint estimations by proposing an assessment of greenhouse gas footprints to the detailed productive sectors of the Brazilian economy for the period 1995-2009, as well as to quantify GHG emissions that arise from the domestic inter-relationship between sectors. This, on its turn, aims to shed light into the responsibility of each sector into the making of a national emissions estimation. Naturally, the total level of a sector's production and consumption of emissions will depend on the total national emissions, which can be measured in either PBA or CBA values. Since the purpose of this work is to obtain the footprint of sectors, the results will refer to a CBA estimate, thus they will include imports and exclude export related GHGs.

In addition, the emissions that have been assigned previously to sectors from a national CBA system, that is, its production plus imports, as done in Kander et al. (2015) will be referred in this work to an activity's *output-based* emissions, since it includes the emissions from the sector's output. The footprint estimates will equal the sector's total consumption plus imports and will be referred to as its *input-based* emissions, since it includes the pollution embedded in its input requirements. Finally, in order to appropriately capture the intersectoral relationships, this study will classify sectors as *net producers* of emissions when they generate more GHGs than they require as inputs for production, and as *net consumers* when they require larger amounts of emissions embodied in inputs than they generate through their production. This paper aims to fill its purpose by addressing the following questions:

(1) *What were the GHG footprints of the productive sectors in Brazil throughout the period 1995-2009?*
    a. *Can the service sector still be regarded as less polluting than others in absolute terms when its complete footprint is taken into account?*

(2) *Comparing the original output-based estimates with the actual footprint of economic activities, which sectors emerge as net producers and net consumers of emissions?*

   a. *Does emission responsibility of sectors change under such classification?*

The remainder of the paper is structured as follows: section 2 will outline the main literature within Environmental Kuznets Curve, service transitions and inter-sectoral relations, followed by a review of the main studies that have estimated Brazilian emissions. Section 3 will introduce the WIOD dataset used for the calculations as well as describe the main variables under study. Section 4 outlines the calculation procedures. Section 5 presents a description of the results obtained, followed by section 6 which offers a discussion and analysis of the results. Finally, section 7 concludes the work and provides policy implications, limitations and areas for future research.

2 Theory

2.1 EKC and the Role of Services

The Environmental Kuznets Curve (EKC) hypothesizes that environmental degradation and economic growth follow an inverted U-shaped relationship, that is, pollution and other indicators of environmental quality worsen at the early stages of a country's developmental path, but start improving after a certain threshold of national income is surpassed (Kaika & Zervas, 2013; Dinda, 2004). It posits that the road to environmental betterment can be achieved best through increased economic activity (Dinda, 2004). The idea that the environment gets worse before it gets better over the course of increased per capita income was first empirically observed in a working paper by Grossman and Krueger (1991), and in subsequent published articles (e.g. Grossman & Krueger, 1995), where the authors observed that economic growth alleviates pollution problems at high levels of income, but it deteriorated the environment at low levels of per capita GDP (Grossman & Krueger, 1991, 1995). It was however, Panayotou (1993) who first coined the term "Environmental Kuznets Curve" (EKC) establishing a parallel between the relationship GDP and environment; and the proposed pattern of income inequality and GDP growth laid out previously by Simon Kuznets, where inequality and development would exhibit an inverted U-shape (Kuznets, 1955).

Authors have speculated on the underlying causes for the observed EKC pattern, where some of the reasons would lie with the characteristics of international trade; the increase demand for a clean environment that follows higher incomes; and the process of technological improvement (Dinda, 2004). One of the most prominent reasons, however, was debated to be the natural cycle of economic development from a low polluting agrarian society to a pollution intensive industrial economy to finally a clean service economy (Kaika & Zervas, 2013; Dinda, 2004; Stern, 2004). Panayotou (1993), in the formulation of the concept of EKC, has pointed out himself that structural changes alone could explain the inverted U-shape of the EKC. Structural change, also referred to the composition effect, argues that the onset of economic growth would first intensify extractive activities in an agrarian society towards an industrial based-economy, but at higher stages of development, the economic system would move to information-based industries and services, which were presumably much less resource intensive and pollutive than the other stages, thus accounting for the downward slope in the EKC (Kaika & Zervas, 2013; Dinda, 2004; Panayotou, 1993).

Panayotou, Peterson and Sachs (2000) attempted to rule out the theory that people have higher demands for a clean environment at higher income levels (i.e. clean environment as an income-elastic amenity), based on that people would need to perceive the presence of pollution in order to demand its removal. However, they argued that pollution in which was not perceptive to people have also followed an inverted U-shape (Panayotou, Peterson & Sachs, 2000). They have also argued that, although international trade could contribute to an apparent national reduction in pollution, it could not explain the persistence of an EKC over their longer timeseries dataset for OECD countries, thus arguing that a service transition was the main factor reducing a country's environmental impact (Panayotou, Peterson & Sachs, 2000). Despite studies measuring the presence of EKC obtaining contradictory results (Kaika & Zervas, 2013; Dinda, 2004) and arguments made that the statistical methods used in empirical observations of EKC were weak (Stern, 2004), the structural change theory remained important and a transition to a service-based economy has been propagated as one of the main roadmaps to mitigating the impacts of climate change (Pacala & Socolow, 2004).

However, sectors experience a high degree of interdependency, where the total national greenhouse gas emissions of a country significantly depend on the sales and purchases of inputs for production between sectors (Tarancón Morán & del Río González, 2007). This effect is usually demonstrated through the behavior of service provision in an economy, where the majority of GHG emitted are not due to the provision of services themselves, but due to their input requirements (Larsen & Hertwich, 2009; Suh, 2006). Larsen and Hertwich (2009) have estimated that 93% of GHG emissions of municipal services in the city of Trondheim, in Norway, are indirect emissions steaming form upstream paths in the value production. Based on their results, they argue the case for introducing a footprint indicator for sectors as a more suitable approach to measure their environmental impact, as opposed to direct production indicators (Larsen & Hertwich, 2009). Similarly, Suh (2006) has calculated that household consumption of services in the United States were responsible for almost 40% of total industrial GHG emissions, when supply-chain effects are considered. Services are anchored to manufacturing outputs (Suh, 2006). An increase in service demand will lead to an increase in industrial production, which contradicts the idea of an environmental relief through a service transition – unless services become independent of GHGs embedded in industries (Suh, 2006). This is in line with more recent reviews that services happen on top of the economic structure since they do not substitute the production of other sectors, but increase them instead (Parrique et al., 2019).

Alcántara and Padilla (2009) perform a carbon flow analysis of sectors in Spain, with a particular emphasis on services. They conclude that the service sector has a strong pull effect on other economic industries, where significant amounts of production are undertaken to serve the final demand of service provision (Alcántara & Padilla, 2009). On the other hand, the transportation sector appears with the highest level of direct emissions compared to other service provisions (Alcántara & Padilla, 2009). The emissions generated in transportation, however, are mostly triggered by other sectors rather than to serve the transportation's own final demand (Alcántara & Padilla, 2009). Thus, in this case, services and transportation would appear with respectively higher and lower footprints than their direct production emissions for which they are commonly assigned to, since estimating sectoral footprints would shift the responsibility for pollution to activities that demanded and consumed the emissions (Minx et al., 2009).

2.2 Emissions from the Brazilian Economy

Early studies focusing on estimating anthropogenic emissions as a result of economic activities in Brazil have paid special attention to international trade (Machado, Schaeffer & Worrell, 2001; Schaeffer & de Sá, 1996). Schaeffer and de Sá (1996) have estimated that Brazil moved from being a net-importer to a significant net-exporter of carbon emissions embodied in goods in the beginning of 1980s. Machado, Schaeffer and Worrell (2001) have also confirmed that Brazil has exported more emission in 1995 than it imported. The environmental burden of emissions were being transferred from developed to developing nations through the consumption of exports produced in emerging markets, which was a result of structural changes in both regions, that is, an expansion of the industrial sectors in Brazil and a transition to service-led economies in developed nations (Schaeffer & de Sá, 1996).

However, more recent developments have challenged such conclusions by taking national technological differences into account, unveiling a different pattern of global carbon trade, and consequently different results for Brazil. Kander et al. (2015) shows that when technology differences are considered, the role of emerging economies become heterogeneous. In the case of Brazil, taking technologies such as renewable ethanol into the accounting procedures, has led to significantly smaller export emissions in comparison to its import ones (Kander et al., 2015). Baumert et al. (2019) shows similar results, where Brazil's production-based emissions are closer to its consumption-based estimates, thus contradicting the results which suggested a transfer of emissions between developed and developing countries (Baumert et al., 2019; Kander et al., 2015).

The estimation of greenhouse gas emissions in Brazil show that one of the most significant shares of emissions arise from Land Use Change and Forestry (LUCF) activities[1] and, that out of the productive sectors of the economy, most emissions come from gases other than carbon dioxide (CO_2); mainly methane (CH_4) and nitrous oxide (N_2O) originating from agricultural production (de Azevedo et al., 2018; Cerri et al., 2009). Some studies analyzing international trade of Brazil have attempted to include emissions from deforestation (Karstensen, Peters & Andrew, 2013) as well as GHGs (Zaks et al., 2009). Since most of Brazilian exports are tied to agricultural and food industry products, these estimations have led to a significantly higher emissions embodied in Brazilian exports and, thus, a larger footprint for countries importing Brazilian goods (Karstensen, Peters & Andrew, 2013; Zaks et al., 2009).

In addition to studies measuring the emissions generated in the country and through international trade, the study of emissions on a sectoral basis in Brazil have attributed responsibility for pollution entirely based on the sector's production. Machado, Schaeffer and Worrell (2001) find that iron and steel; transportation; and chemicals have had the largest carbon intensities in Brazil (i.e. carbon per dollar of output), whilst, services, textile and clothing, as well as agriculture and livestock were found with the lowest CO_2 intensities. Nonetheless, when other GHGs are added, the pollution-intensity estimates change

[1] Land Use Change and Forestry (LUCF) include activities such as forest and grassland conversion and emissions and removals from soils (Cerri et al., 2009).

significantly. de Souza, Ribeiro and Perobelli (2016) found that over 50% of total national emissions are from livestock alone and another 17% from transport and postal activities. de Souza, Ribeiro and Perobelli (2016) argue that GHG emissions in Brazil are highly concentrated in a handful of sectors, and have estimated that the lowest reduction on total national output from GHGs mitigation policies would primarily affect the output of the most GHG intense activities (such as livestock and cement production), and that services would not be affected by output restrictions since its GHG intensities are far too low. On one hand, de Jesus Teixeira et al. (2020) also report a low contribution of service activities, where its aggregated impact was responsible for 0.2% of total GHG emissions reported in 2011. On the other hand, the authors have also estimated the indirect impact of services – through their demands on the other sectors – which led to a re-estimation of the sector's contribution to 13% of national emissions (de Jesus Teixeira et al., 2020).

3 Data

3.1 Input and Output Emissions

The estimation of a country's emissions can be done on a production or a consumption account (PBA and CBA), thus assigning emissions by sector can also be done on a production or consumption base, depending on where the burden of pollution is placed (Minx et al., 2009). The calculation of a sector's production-based emissions represents the total GHGs emitted by this activity in order satisfy the total demand of industrial and non-industrial consumption. In order to avoid confusion between terminologies, this paper will define *output-based* emissions as the GHGs emitted by the production of an industry or activity. It will conversely define *input-based* emissions as the GHGs embodied in the total required consumption of a sector for it to deliver its production. Naturally, the total level of a sector's consumption and production will change whether exports or imports are included, but since CBA represents a national footprint, this work will primarily estimate total sectoral footprint based on the national total consumption (i.e. CBA). This, however, does not impede the calculation of a sector's footprint when the level of final demand changes to include exports. Table 3.1 shows sectoral output and input emissions under both a PBA and CBA accounts.

Table 3.1 Output and Input Emissions in PBA and CBA

	PBA		CBA	
	Output emissions	Input emissions	Output emissions	Input emissions
Sector x	a_1	b_1	c_1	d_1
Sector y	a_2	b_2	c_2	d_2
Sector w	a_3	b_3	c_3	d_3
⋮	⋮	⋮	⋮	⋮
Sector n	a_n	b_n	c_n	d_n
Total	$\sum_{i=1}^{n} a_i$	$\sum_{i=1}^{n} b_i$	$\sum_{i=1}^{n} c_i$	$\sum_{i=1}^{n} d_i$
	$\sum_{i=1}^{n} a_i = \sum_{i=1}^{n} b_i$		$\sum_{i=1}^{n} c_i = \sum_{i=1}^{n} d_i$	

Under a PBA account, output emissions include the GHGs embodied in the production of each individual sector, including the production it delivers for exports. The input emissions will equal the industry's total consumption, including the extra input it requires to meet the demand for exports. Under a CBA account, input emissions include a sector's total consumption, including the imports it used as inputs for production. The output emissions, on the other hand, also include imports and they refer to the total GHGs embodied in the production of each domestic sector, plus the emissions produced by the equivalent sector that exported to Brazil. The results will be discussed under a CBA account, which refers to the highlighted right-hand side of Table 3.1, thus in summary, its input-based estimates reflect a full sectoral footprint calculation, however the treatment of imports for an output-based account will follow the approach to assign sector responsibility based on its production plus its imports as done in Kander et al. (2015).

It can be questioned whether it would not be more appropriate to estimate input emissions only within a CBA account and output emissions only within a PBA system. However, the two indicators' difference would then be primarily the result of international trade effects. The estimation of output and input emissions within the same national total considers emissions from international trade but cancels out its effect on explaining the differences between output and input emissions, which then reflect only the pattern of demand and production of a sector. As shown in Table 3.1, for both PBA and CBA estimates, the sum of all sectors output emissions equals the sum of all input emissions, because the estimation of input emissions shifts part of the burden of pollution to the sectors that consumed it, but it does not alter the national total since they are calculated under the same accounting scheme. Within each sector, a higher output than an input emission implies the sector is a net producer of GHGs, the opposite implies it is a net consumer of GHGs.

The data used for the calculations in this work are taken from the World Input-Output Database (WIOD) 2013 release, since it contains the most recent IO tables from WIOD with related environmental accounts (Timmer et al., 2015; Genty, Arto & Neuwahl, 2012). In addition, this work will measure the country's sectoral greenhouse gas emissions, thus carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are then included. They are bundled together to a CO_2 equivalent amount (CO_2-eq). This procedure is done by converting methane and nitrous oxide into their CO_2-eq using Global Warming Potentials (GWP) estimates provided by the IPCC's forth assessment report (IPCC, 2007). Although there are updated GWP values at the fifth assessment report (IPCC, 2013), the calculation of GWP depends, among other aspects, on the current atmospheric concentration of the gas at hand, thus its equivalent to CO_2 may be updated over time (de Azevedo et al., 2018; US EPA, 2016). Since the time frame of this work comprises of 1995-2009, the estimates from IPCC (2007) are the most suitable for this period (de Azevedo et al., 2018)[2]. Therefore, the gas content of CH_4 and N_2O provided by the WIOD have been multiplied by 25 and 298 respectively – which are their GWP values – to obtain their CO_2-eq content (IPCC, 2007), which were then summed with the values for CO_2 to obtain a metric for total GHG by sector. Finally, WIOD includes the emissions of productive economic sectors, and thus LUCF related impact are not included in the estimates (Genty, Arto & Neuwahl, 2012).

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[2] de Azevedo et al. (2018) estimates Brazilian GHG emission over 1970-2015 and uses three different GWP values throughout the time period.

3.2 Input-Output Table

Input-Output tables are well suited to benchmark calculations of sectoral GHG footprints, because they provide complete and detailed data points of direct and indirect GHG emissions related to the production and consumption of industries in an economy (Minx et al., 2009). Since this study applies a sectoral footprint methodology to the Brazilian case, it makes use of a single-region input-output table illustrated by Table 3.2. The table describes a country with K industries (e.g. mining), k = 1, 2…K, and N final demand categories, which are the demands of non-industrial sectors (e.g. final household consumption) n = 1, 2, … N. The rows of the table provide data on the output production of one sector to another, whereas the columns describe the inputs requirements of an industry from another. The matrix of inter-industry production and consumption flow is referred to as the intermediate delivery matrix **Z**. Imports are provided by sector, below the national industries, and exports are captured as a final demand category.

Table 3.2 Structure of a Single-Region IO Table

		Intermediate imputs (Z)				**Brazilian Final Demand (Y)**			Total Output
		Industry 1	Industry 2	…	Industry K	Final Demand 1	…	Final Demand N	
National output	Industry 1								
	Industry 2								
	…								
	Industry K								
Imported output	Import (1)								
	Import (2)								
	…								
	Import (k)								
Value Added									
Total Output									

Source: own construction based on Timmer et al. (2015) and Wiedmann et al. (2006)

Z = Intermediate delivery matrix, where Z^D and Z^I refer to the domestic and import deliveries. Z^D consists of dimensions K^D x K, and Z^I of dimensions K^I x K.
Y = Final demand matrix where Y^D and Y^I refer to the final national demand for domestic and import outputs of dimensions K^D x N and K^I x N, respectively.
$\mathbf{w}_i$ = vector of value added (including taxes) for sector i, of dimensions 1 x K.
$\mathbf{x}_i$ = Total output of sector i, of dimensions 1 x K, including import inputs.

WIOD provides a table similar to the single-region IO described above. It is constructed of 35 x 35 sectors (K = 35) and 6 final demand categories (N = 6). One sector, named “private households with employed persons”, however, had only zero values for outputs, inputs and emissions for all years and it was thus, removed, resulting in a final 34 x 34 national delivery matrix and 34 x 34 imports delivery matrix.

4 Methods

4.1 Input-Output analysis: a short introduction

Input-Output analysis was pioneered by Wassily Leontief in an attempt to quantify the general idea of interdependence between the various segments of an economic system (Leontief, 1970, 1936). It follows a bookkeeping procedure where a sell in one side must be corresponded by a purchase on the other, reflecting a system where industries produce and absorb goods among themselves in addition to delivering parts of their production to demands of non-industrial sectors (e.g. household or government consumption) (Leontief, 1936). Leontief has also stressed the applicability of IO tables in measuring various forms of economic externalities (Leontief, 1970). By-products are related to a particular production and consumption process, where the amount of pollution follows a definitive relationship to the amount of output of an industry, given a certain level of technological system (Leontief, 1970). This, on its turn, treats emissions as what they actually are: "integral parts of the economic process" (Leontief, 1970, p.270).

4.2 Input-Output application to sectoral footprint

The present work largely builds on the methodology first proposed by Bicknell et al. (1998) as well as subsequent improvements (e.g. Ferng, 2001; Lenzen, 2001; Lenzen & Murray, 2001). Bicknell et al. (1998) were the first to use an input-output method to estimate ecological footprints, which calculates national land disturbance required to sustain present levels of consumption – they then applied their method to New Zealand. Bicknell et al.'s (1998) method makes it suitable for analyzing the impact of consumption on the environment attributable to sectors of other forms of pollutants as well, since the methodological process of estimating sectoral footprints in an IO approach used by Bicknell et al. (1998) is applicable to any form of economic by-product (Lenzen, 1998). Therefore, the method described below will apply greenhouse gas emissions to sectors based both on their required inputs for production to serve final demands (i.e. footprints), as well as the emissions related to their outputs (i.e. their own production). The calculations have been performed following four steps:

I. Prepare standard input-output calculations.

II. Calculate emissions multiplier matrices.

III. Assign emissions to final demand categories.

IV. Obtain sectoral emissions in both inputs and outputs.

I. Prepare standard input-output calculations

The technical coefficient matrix, commonly known as the **A** matrix, is derived by dividing the elements in the intermediate delivery matrix **Z** with the corresponding sector's total output.

$$A = [a_{ij}] = \left[\frac{z_{ij}}{x_i}\right] \quad (1)$$

An element a_{ij} describes the direct amount of input (in monetary terms) from sector *i* to raise output in sector *j* by 1$. The **A** matrix depicts first order requirements, and thus, does not account for indirect changes in production. For instance, an initial increase in production in industry *j* will lead to an increase in demand and thus production in other industries, since sectors are deeply intertwined. Those initial increases in other sectors are referred to first order requirements and they are captured by the direct input values in matrix **A**. However, first order requirements also demand further production, which on its hand will also demand subsequent further production. This cascading effect initiates a chain of economic activity of both first and higher order requirements, which is captured by the Leontief inverse, mathematically written below:

$$\boldsymbol{L} = [l_{ij}] = (I - A)^{-1} \quad (2)$$

Equation 2 above is obtained by subtracting the **A** matrix from an identity matrix **I** of equal dimensions. The result of the subtraction is then inverted, which requires the matrix at hand to be squared (i.e. equal number of rows and columns). An element l_{ij} represents the total (direct and indirect) requirements of sector *i* to raise output in sector *j* by 1$.

II. Calculate emissions multiplier matrices

A multiplier matrix, also referred to as total intensity matrix, assigns greenhouse gas emissions (or another external phenomenon under study, which is compatible with IO tables) to the direct and indirect production values of each sector (i.e. Leontief inverse). Bicknell et al., (1998) and Ferng (2001), apply such method to estimate footprints of both domestically produced products and imported goods, thus assuming identical multipliers for the national production structure and imports. The issue with this method is that equation 2 was estimated based purely on domestic input requirements under their study, and thus leaves out the inputs to the intermediate delivery matrix **Z** from imports (Lenzen, 2001). Lenzen & Murray (2001) argue that ignoring imports inputs would underestimate energy multipliers for Australia by 30%, for instance. One may thus, exclude imports altogether and obtain an environmental impact estimate based on a national production-based accounting (PBA).

However, both Bicknell et al., (1998) and Ferng (2001) include imports in their calculations through estimating footprints with identical multipliers, which leads to significant quantitative errors (Lenzen, 2001; Lenzen & Murray, 2001). Therefore, in order to obtain the appropriate intensity matrices for domestic and import structures, the input coefficients of imports need to be estimated. Let A^D and A^I be the technical coefficient matrices of dimensions 34x34 obtained through equation 1 of, respectively, the domestic and import inputs to the intermediate delivery matrix $\mathbf{Z}$. Through equation 2 we obtain L^D and L^I from the inverse of the result of the subtraction of each technical coefficient matrix from the identity matrix I, representing respectively, the total requirement matrices domestically and imported. In order to assign emissions to the total requirement matrices, first the emissions input coefficients, or direct intensity matrix, is calculated by dividing the vector of emissions by the corresponding sector's total output:

$$\boldsymbol{d_i'} = \frac{g_i'}{x_i} \qquad (3)$$

An element of the vector d_i' represents the greenhouse gas emissions which are *directly* associated with the production activities of a sector, per million dollars of its output (Kt of CO2 eq/M$). Since the present work is also interested in verifying the flow of emissions between sectors, we obtain the diagonalized form of the emissions input coefficient, $\widehat{d_i'}$ as a 34x34 matrix. Postmultiplying $\widehat{d_i'}$ with each direct and indirect production requirement matrix (i.e. Leontief inverses) will result in the two multipliers, written below:

$$\boldsymbol{M^D} = \left[m_{ij}^D\right] = \widehat{d_i'} \cdot L^D \qquad (4a)$$

$$\boldsymbol{M^I} = \left[m_{ij}^I\right] = \widehat{d_i'} \cdot L^I \qquad (4b)$$

Therefore, an element m_{ij}^D or m_{ij}^I represents the direct and indirect greenhouse gas emissions produced over the entire value chain to generate an additional unit of output to final demand, in millions of dollars (Kt of CO2 eq/M$) (Wiedmann et al., 2006). Utilizing $\boldsymbol{M^D}$ to estimate import emissions (as in the case of Bicknell et al., 1998 and Ferng, 2001) is the equivalent of assuming that inputs from imports enter the national intermediate delivery matrix $\mathbf{Z}$ in equal proportions as national production. In the case of Brazil, $\boldsymbol{M^D}$ is considerably higher than $\boldsymbol{M^I}$ throughout the period, and assuming identical multipliers would have overestimated import emissions and, thus, sectoral footprints when measured under a national consumption-based accounting (CBA). Due to the current availability of a more complete import matrix structure from WIOD (Timmer et al., 2015), the $\boldsymbol{M^I}$ can be estimated, which corrects this error in the original methodology (Lenzen, 2001; Lenzen & Murray, 2001; Machado, Schaeffer & Worrell, 2001)[3].

III. Assign emissions to final demand categories.

In order to calculate sectoral emissions that serve a given consumption determined by the final demand categories, $\boldsymbol{M^D}$ and $\boldsymbol{M^I}$ are postmultiplied with the corresponding diagonalized vectors of each final demand for domestically produced goods, $\widehat{y_n^D}$ and imported goods, $\widehat{y_n^I}$, resulting in the emissions to final demand matrices $\boldsymbol{EF_n}$:

$$\boldsymbol{EF_n^D} = \left[ef_{ij}^D\right] = M^D \cdot \widehat{y_n^D} \quad (5a)$$

$$\boldsymbol{EF_n^I} = \left[ef_{ij}^I\right] = M^I \cdot \widehat{y_n^I} \quad (5b)$$

Equations 5a and 5b – as with 4a and 4b – are essentially the same, they are split to illustrate that the domestic multiplier, $\boldsymbol{M^D}$, is used when addressing final demands for goods produced domestically, $\boldsymbol{Y^D}$, the same logic applies to imports. This, on its turn, leads to 34x34 sector-by-sector matrices, which its elements, ef_{ij}, represent the total greenhouse gas emissions produced in sector *i* to sector *j* to serve a final demand *n* in millions of dollars (Kt of CO2 eq/M$).

IV. Obtain sectoral emissions in both inputs and outputs.

Following the third step, the total national emissions on a sector base, $\boldsymbol{E^{tot}}$, is obtained by summing the matrices of emissions to each final demand. Thus, they can be obtained in PBA and CBA national values:

$$\text{PBA: } \boldsymbol{E_{PBA}^{tot}} = \left[e_{ij}^{tot}\right] = \sum EF_n^D \quad (6)$$

$$\text{CBA: } \boldsymbol{E_{CBA}^{tot}} = \left[e_{ij}^{tot}\right] = \left(\sum EF_n^D - EF_{exp}^D\right) + \sum EF_n^I \quad (7)$$

EF_{exp}^D is the matrix of emissions related to export goods, which is subtracted from total domestic emissions, and subsequently, import emissions are added to obtain the greenhouse gas values in CBA (Kander et al., 2015; Peters & Hertwich, 2008). The results of this work are presented

[3] It is worth noting that Machado, Schaeffer and Worrell (2001) also use the same multiplier for imports as for domestic emissions. However, in their case, that is motivated by their research purpose to measure energy and emissions "saved" if Brazil were to produce its imports. They further acknowledge that, otherwise, an appropriate multiplier should be calculated based on IO tables of the exporter countries.

mainly to what refers to equation 7, the results of equation 6 are provided in appendix A for comparison reasons. Therefore, $\boldsymbol{E^{tot}}$ is a 34x34 matrix where its elements e_{ij}^{tot} describe the total GHG emissions embodied in the production of sector *i* to sector *j* in order to satisfy total final demand of a country (Kt of CO2 eq/M$). Finally, a sector's footprint emissions is obtained through summing up the elements e_{ij}^{tot} over *j* (Ferng, 2001), which are the inputs for production for a particular sector, and output emissions are obtained through summing up the elements e_{ij}^{tot} over *i*, which are the production that a particular sector delivers to others. This can be written in matrix notation as:

$$Input\ emission\text{: } \boldsymbol{\alpha_{ij}} = v_{ij} \cdot E_{CBA}^{tot} \tag{8}$$

$$Output\ emissions\text{: } \boldsymbol{\beta_{ij}} = E_{CBA}^{tot} \cdot v_{ij}^{T} \tag{9}$$

v_{ij} is a vector of dimensions 1x34 where all its elements equal 1. Postmultiplying v_{ij} with E_{CBA}^{tot} obtained in equation 7, results in vector $\boldsymbol{\alpha_{ij}}$ also of dimensions 1x34, where each of its elements are the sum of the emissions embodied in all deliveries to a sector. It represents the emissions embodied in a sector's total consumption, including the consumption it obtains from itself, and therefore it represents a sector's footprint (Minx et al., 2009). v_{ij}^{T} is the transposed form of v_{ij} and, thus, has dimensions 34x1. Premultiplying v_{ij}^{T} with E_{CBA}^{tot} leads to the vector $\boldsymbol{\beta_{ij}}$, where its elements represent the sum of all that a sector produced to other industries to serve final demand. It essentially represents a sector's production-based emissions, but this term could cause confusion since the country's greenhouse gases are measured in a consumption-base, therefore they are referred to in this work as output emissions. The values obtained from $\boldsymbol{\alpha_{ij}}$ and $\boldsymbol{\beta_{ij}}$, and their comparison lie at the core of the analysis of this work. The sum of the resulting elements in equation 8 equals the sum of the resulting elements in equation 9 by providing the total national estimate either in PBA or CBA. The results of equation 9, if performed under the values of a PBA analysis in equation 6, equal the sectoral emissions estimated by the WIOD (Genty, Arto & Neuwahl, 2012), which underpins the reliability of the methodology applied.

Finally, it is important to highlight some of the limitations regarding the dataset and the methodology used. First, the WIOD sectoral resolution is reasonable with 35 sectors for these initial estimations, but it is not at all exhaustive. The aggregation of sectors my lead to certain biases regarding its emissions because it may assign responsibility to the broad classification rather than to specific activities. For instance, agriculture, hunting, forestry, and fishing are bundled together, as one disaggregated sector. However, emissions relating to fishing may significantly differ from those of agriculture, as well as defining the activities within agriculture that leads to pollution will have to remain speculative, rather than empirical, which naturally constrains some of the conclusions that can be derived from the results. Another limitation refers to employing a Single-Region IO table to the estimates. Lenzen, Pade and Munksgaard (2004) show that the required aggregation of data points to construct a Single-Region IO table leads to a significant increase in uncertainty and possible quantitative differences if compared to Multi-Region IO tables. Since the purpose of the work was to analyze sectoral pollutions, applying a Multi-Region IO table would have required the analysis of all sectors from all importing countries to Brazil, which would have consumed a significant amount of time. Nonetheless, to allow comparability with other studies and estimates, this work has performed the calculation of the results under a PBA system. Appendix A shows the results in PBA and appendix B compares the national total obtained in this study with the estimates done by the OECD (2020) and the SEEG project, which represent the most recent official estimations by the Brazilian Climate Observatory (de Azevedo et al., 2018). The results are in sharp line with the two official estimations, which renders this study some level of accuracy.

5 Results

The tables and figures in this section reflect the author's own calculation. Table 5.1 presents the output emissions; emission footprints; and their percentage difference for the year 2008, which was chosen as the year to present the disaggregated sectoral data, since there is an observable drop in emissions in 2009 (see appendix A), likely the result of the international financial crisis (de Souza, Ribeiro & Perobelli, 2016) . Figure 5.1 shows the results for the entire period under a broad sectoral aggregation. WIOD uses the International Standard Industrial Classification revision 3 (ISIC Rev. 3) for its sector classification (Timmer et al., 2015). This study has aggregated them based on the International Labour Organization's broad sector concordance of the ISIC Rev. 3 (ILOSTAT, 2020). The ILO considers transportation activities to be part of services, however, for environmental analysis, it makes sense to separate the two, since they may show different trends (Kander, 2005). Thus, activities defined as "transportation" by the ISIC Rev.3 (which include post and telecommunication) were separated from other private and public services. See appendix C for each broad sector classified in this study.

Table 5.1 Output emissions; input emissions and their percentage difference for all sectors in 2008 under a national CBA system.

		Column 1		Column 2		Column 3
Reference number.		GHG emissions (Output-based) in kt of CO2-eq		GHG Footprints (Input-based) in kt of CO2-eq		% Δ
c1	Agriculture, Hunting, Forestry and Fishing	416 544		186 120		-55%
c2	Mining and Quarrying	20 584		254		-99%
c3	Food, Beverages and Tobacco	4 831		172 023		3461%
c4	Textiles and Textile Products	2 234		8 163		265%
c5	Leather, Leather and Footwear	354		2 838		702%
c6	Wood and Products of Wood and Cork	324		488		50%
c7	Pulp, Paper, Paper, Printing and Publishing	3 512		5 371		53%
c8	Coke, Refined Petroleum and Nuclear Fuel	19 571		21 249		9%
c9	Chemicals and Chemical Products	16 719		17 492		5%
c10	Rubber and Plastics	915		679		-26%
c11	Other Non-Metallic Mineral	21 608		2 164		-90%
c12	Basic Metals and Fabricated Metal	22 126		8 493		-62%
c13	Machinery, Nec	1 215		10 226		742%
c14	Electrical and Optical Equipment	2 033		7 759		282%
c15	Transport Equipment	1 191		13 685		1049%
c16	Manufacturing, Nec; Recycling	739		4 907		564%
c17	Electricity, Gas and Water Supply	24 758		13 882		-44%
c18	Construction	3 922		31 098		693%
c19	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	733		1 514		106%
c20	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	1 253		4 330		246%
c21	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	5 505		8 387		52%
c22	Hotels and Restaurants	1 698		32 753		1829%
c23	Inland Transport	31 953		19 419		-39%
c24	Water Transport	6 719		3 248		-52%
c25	Air Transport	1 906		1 326		-30%
c26	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	3 457		4 096		18%
c27	Post and Telecommunications	2 210		5 755		160%
c28	Financial Intermediation	488		5 810		1091%
c29	Real Estate Activities	357		2 244		529%
c30	Renting of M&Eq and Other Business Activities	4 375		10 527		141%
c31	Public Admin and Defence; Compulsory Social Security	7 978		31 155		290%
c32	Education	2 693		12 465		363%
c33	Health and Social Work	1 860		15 683		743%
c34	Other Community, Social and Personal Services	60 464		31 228		-48%
	Total	696 830		696 830		

The estimation presented in Table 5.1 has calculated sectoral emissions based on a national CBA system, which means that exports were excluded, and imports were added to the values, which reflect the highlighted section of Table 3.1 in the Data section. Table 5.1 presents a snapshot into one of the years studied – 2008 – showing the highly disaggregated results for the two emission accounting systems. Column 1 presents sectoral GHG emissions calculated using the output-based approach. The values under column 1 represent the emissions that are attributable to a sector's total production. For instance, in the case of agriculture (reference number c1 in the table), it includes emissions from the production of milk, which can include the methane released by cows during the process. In column 2, sectoral results for the input-based approach are shown. It provides the emissions embodied in the total consumption of a sector, including the consumption from the production it produces and absorbs itself, and thus represents a footprint indicator. For example, the emissions for the food, beverages, and tobacco industry (c3) in column 2, represent the GHGs embodied in the total input requirements that the food industry consumes in other to generate a certain level of output. The environmental impact from milk production would then enter as an input pollution to the dairy industry.

The two indicators are followed by column 3 which provides the percentage change in emissions from the output to the input estimators by sector. A negative sign represents the percentage reduction from output to input-based accounts and shows that the sector is a net *producer* of emissions, that is, the GHGs embodied in its production are higher than the GHGs embodied in its consumption. A positive sign, on the other hand, shows that the sector is a net *consumer* of emissions. The sum of all sectors, which equals the total national emissions, is showed in the final row. The value is identical for both output and input emissions, reiterating that the estimation of input emissions affects the GHG responsibility of sectors, without altering the national total.

Table 5.1 shows significant sectoral differences between output and input indicators. Some sectors, such as hotels and restaurants (c22), emerged with an extremely high footprint as compared to a standard output measure (with approximately 1,829% change). This outlines that hotels and restaurants are a net consumer of GHGs. Output emissions take into consideration that the sector emits 1,550 kt of CO_2-eq through its direct service provision but misses to quantify that it also demands 27,474 kt CO_2-eq from agriculture, hunting, forestry and fishing (AHFF) (Table 5.2). Other sectors, such as chemicals and chemical products (c9) experience little change between the indicators. Table 5.2 and 5.3 show in more detail the makeup of input and output emissions for the hotels and restaurants, and chemicals and chemical products sectors[4]. Under input emissions, it shows the amount and the sectors from where they purchased goods and their embodied GHGs (origin), followed by the total input emissions. Under output emissions, it shows the amount and the sectors to which they sold their outputs and embodied GHGs (destination), followed by the total output emissions for the year 2008.

[4] The detail flow of emissions sector-by-sector for all years, as well as the split of GHGs by final demand categories is available from the author upon request.

Table 5.2 Detailed makeup of indicators for hotels and restaurants sector

Hotels and Restaurants			
Input emissions		**Output emissions**	
Origin			**Destination**
Agriculture (AHFF). (c1)	27 474	1 550	Hotels and Restaurants (c22)
Hotels and Restaurants (c22)	1 550	148	Rest of sectors
Rest of sectors	3 729		
Total input emissions (kt CO_2-eq)	32 753	1 698	Total output emissions (kt CO_2-eq)

Table 5.3 Detailed makeup of indicators for chemicals and chemical products sector

Chemicals and Chemical Products			
Input emissions		**Output emissions**	
Origin			**Destination**
Agriculture (AHFF). (c1)	2 987	1 159	Food, Beverages and Tobacco (c3)
Mining and Quarrying (c2)	1 263	1 017	Health and Social Work (c33)
Chemicals and Chemical Products (c9)	8 755	8 755	Chemicals and Chemical Products (c9)
Rest of sectors	4 487	5 788	Rest of sectors
Total input emissions (kt CO_2-eq)	17 492	16 719	Total output emissions (kt CO_2-eq)

In addition to analyzing the results of the disaggregated sectors, figure 5.1 presents the GHG emissions under a broad sectoral classification, and their results for output and input-based emissions on the top and bottom graphs, respectively. The two graphs first show that emissions responsibility is more proportionally distributed across the broad economic sectors under a footprint account, whereas under an output-based system, GHGs are concentrated mostly in the agricultural sector. Agriculture was responsible for emitting a yearly average of 61% of Brazil's total GHG emissions over the 1995-2009 period studied under an output-based system, however its footprints have averaged approximately 25.8% yearly (Figure 5.1). This means that the sector produces significantly more emissions to serve the demand of other industries than it requires for its own production. The service sector, on the other hand, shows an opposite trend. Its output emissions have averaged 12.7% of the national total over the period, whilst its footprint rose to 23%. Therefore, the service sector generates emissions through demanding production across the economic value-chain, and its consumption is responsible for a similar level of pollution as the agriculture's footprint. This outlines the characteristics of agriculture and services in being net producers and net consumers of emissions respectively in Brazil over the period studied.

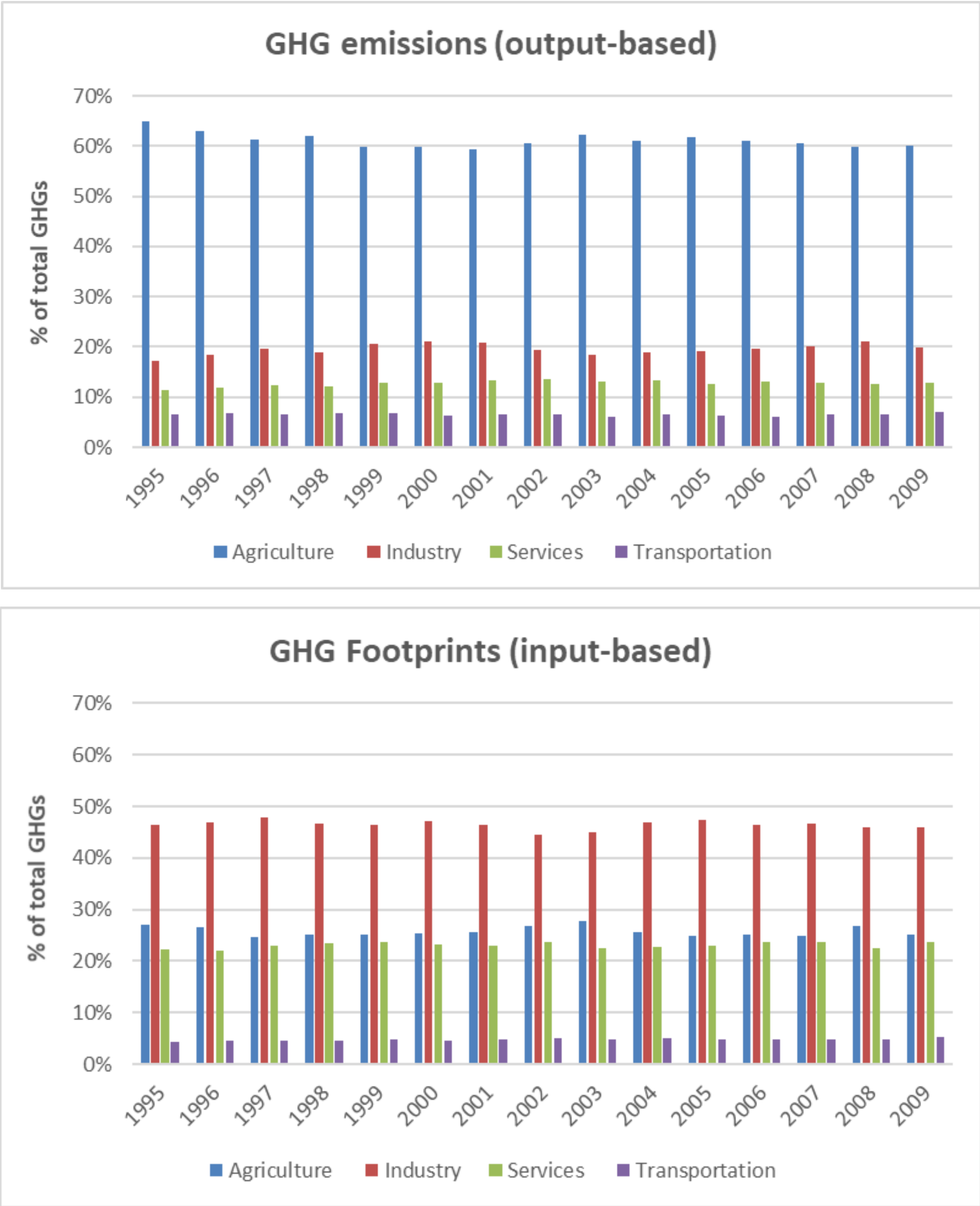

Figure 5.1 GHG emissions under a broad sectoral aggregation in output and input indicators (1995-2009) under a CBA national value.

In figure 5.1, the transportation sector appears proportionally low due to the inclusion of methane (CH_4) and nitrous oxide (N_2O), which disproportionally increase the output emissions of the other sectors in relation to transportation – specially in agriculture and some industrial processes – (de Azevedo et al., 2018; Genty, Arto & Neuwahl, 2012). According to the environmental accounts provided by the WIOD for which this work builds upon, the combined emissions of CH_4 and N_2O (in CO_2-eq) are almost three times higher than the total emissions in CO_2, in 2008 (Genty, Arto & Neuwahl, 2012). The dataset shows that transportation activities do not emit as much of the other gases as other sectors do (Genty, Arto & Neuwahl, 2012).

Therefore, although the direct carbon content of transportation activities is very high, when other greenhouse gases are considered, its output emissions appear to be proportionally low to the other sectors. Additionally, under an input estimation, its footprint becomes even lower. The disaggregated transportation sectors c23, c24 and c25 in Table 5.1 are net producers of emission, reflecting a transportation pattern of generating emissions that are consumed by the final demand of other sectors.

The large scale use of renewable ethanol in Brazil for the transportation sector naturally reduces its output emissions, where the direct impact of ethanol use in transportation has been assigned a zero for carbon emissions in some studies (e.g. Machado, Schaeffer & Worrell, 2001). Additionally, the agricultural and industrial impact of its production which enters as inputs for the sector can also be low in its GHG content, compared to petroleum based fuels (Cerri et al., 2009). First, to produce ethanol, the sugar cane stalks are crushed to obtain the cane liquid, whilst the cane residue, called bagasse, is burnt to generate steam and electricity for some of the mill factories (Cerri et al., 2009). In addition, the wastewater from alcohol production can be converted to methane through anaerobic digestion, where some of the transportation fleet in sugar factories and alcohol distilleries are powered by methane (Cerri et al., 2009)[5], thus significantly reducing the pollution byproduct assigned to the transportation's input estimates.

In its aggregated form, the industrial sector emerged with the largest GHG footprints in Brazil in all years (Figure 5.1), with its input emissions being approximately 238% higher over the period than its output emissions. However, when analyzing the disaggregated sectoral results in Table 5.1, it is possible to observe that the underlying reason for the sharp increase in emissions responsibility of industry is significantly due to the behavior of the food, beverages and tobacco sector (c3) – FBT – which is part of industry under the broad sectoral classification (see appendix C). On the third column of Table 5.1, FBT experienced a striking 3461% change in total emissions between its output and footprint indicators, and thus has emerged as the most significant net consumer of emissions in the country. Figure 5.2 below shows the emissions of FBT against the aggregated rest, where "industry" includes the remaining 16 sectors.

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[5] It is important to note that not all sugar cane plantation follows the same process. Emissions can in fact be much higher if the harvesting of the plant applies techniques of soil burning, which leads to unnecessary pollution, however, the data estimates for such process is scarce (Cerri et al., 2009). Cerri et al. (2009) estimates that 8 000 kt of carbon are avoided only by using the plant residue for electricity generation.

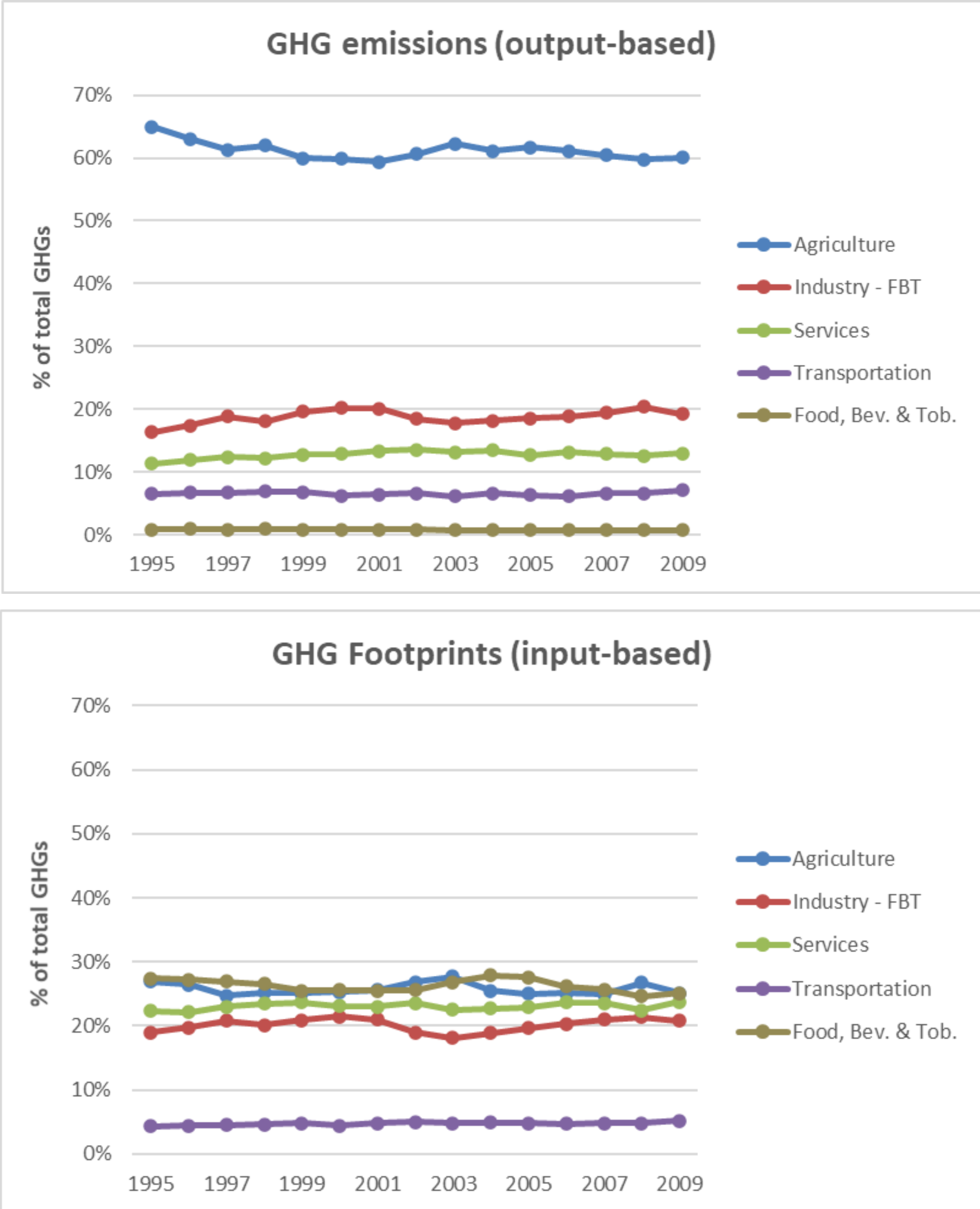


Figure 5.2 Comparison of FBT with other aggregated sectors under a national CBA value.

Emissions responsibility remain more proportionally distributed between sectors in a footprint approach in figure 5.2, but other sectoral characteristics change as compared to figure 5.1. First, the average footprint of industries over the period is only 7.5% higher than its output emissions, as it is also lower than agriculture and services in all years. Food, beverages and tobacco, which, on the other hand, would only be responsible for 0.7% of output related greenhouse gas production in Brazil in 2008, its footprint accounted for almost 25% of total national emissions in the same year. Alone, FBT appeared as the largest contributor to emissions in most years studied, apart from years 2001 to 2003; 2008 and 2009, where agriculture was slightly higher. Output emissions captured the GHGs embodied in the production of FBT to other sectors but missed the bulk of its indirect environmental impact: agricultural demand. In the year 2008, FBT consumed an equivalent of 157 019 kt CO_2-eq from the agricultural sector alone, which corresponds to over 91% of FBT's total footprint.

Table 5.4 Detailed makeup of indicators for food, beverages and tobacco sector

Food, Beverages and Tobacco			
Input emissions		**Output emissions**	
Origin			**Destination**
Agriculture, HFF. (c1)	157 019	3 869	Food, Beverages and Tobacco (c3)
Food, Beverages and Tobacco (c3)	3 869	498	Hotels and Restaurants (c22)
Other Community, Social and Personal Services (c34)	2 610	102	Agriculture, HFF. (c1)
Inland Transport (c23)	1 379		
Rest of sectors	7 146	362	Rest of sectors
Total input emissions (kt CO2-eq)	172 023	4 831	Total output emissions (kt CO2-eq)

Therefore, reconnecting the results thus far with the first proposed research question of this study, question 1 was defined as:

(1) *What were the GHG footprints of the productive sectors in Brazil throughout the period 1995-2009?*
   a. *Can the service sector still be regarded as less polluting than others in absolute terms when its complete footprint is taken into account?*

The GHG footprints of sectors in Brazil were estimated for the period 1995-2009 using an input-output approach. By taking all the sectors full consumption pattern into account, the economic activities in the country showed a significantly different output emissions from their input estimates, revealing that large shares of production undertaken by certain sectors were in fact demanded by other activities, which would traditionally reveal a low pollution content in its production. The service sector's footprint was found to be higher than the aggregated 16 industrial sectors (i.e. excluding FBT), reaching a similar impact as agriculture, which is commonly considered the most polluting sector in the country. The total impact of services fluctuated between 22% and 24% of national emissions throughout the period, and therefore it cannot be considered cleaner or less polluting in absolute values than other sectors of the economy.

The second question, on the other hand, was concerned with:

(2) *Comparing the original output-based estimates with the actual footprint of economic activities, which sectors emerge as net producers and net consumers of emissions?*

a. Does emission responsibility of sectors change under such classification?

The classification of sectors as net consumers or net producers of GHGs, which arises from the estimation of both output and input emissions, unveils intersectoral relations that underpin the demand for and production of emissions in the country. Table 5.5 and 5.6 show the sectors that emerged as net producers and net consumers of GHGs, respectively. They are organized from the most producer/consumer of emissions to the lowest. Column 1 in both tables show the difference between the sector's output and input estimates and column 2 shows the percentage share of their result within the net produced/consumed totals.

Table 5.5 Sectors classified as net producers of emissions

		Column 1	Column 2
Reference number		Output - Input (in kt of CO2-eq)	Share of total net-produced emissions
c1	Agriculture, Hunting, Forestry and Fishing	230 424	68%
c34	Other Community, Social and Personal Services	29 236	9%
c2	Mining and Quarrying	20 330	6%
c11	Other Non-Metallic Mineral	19 444	6%
c12	Basic Metals and Fabricated Metal	13 633	4%
c23	Inland Transport	12 534	4%
c17	Electricity, Gas and Water Supply	10 876	3%
c24	Water Transport	3 471	1%
c25	Air Transport	580	0%
c10	Rubber and Plastics	236	0%
	Average	34 076	
	Total GHGs produced to other sectors	340 763	

The final row in Table 5.5 presents the total GHGs produced by the above sectors which were delivered to others across the productive structure of the economy. The "excess" generation of emissions in Table 5.5 equal the "excess" consumption by activities in Table 5.6, which is 340 763 kt of CO_2-eq. If we compare this value to the total national CBA estimates (Table 5.1), we can observe that half of the country's GHGs were embedded in a domestic inter-sectoral trade, thus their consideration in estimating sectoral footprints cannot be ignored. The remainder of national emissions include those which were absorbed by the same activity that produced it, plus imports. This estimation, nonetheless, partially reflects the level of sectoral aggregation employed in this study. A more detailed sectoral definition would reduce the emissions which were absorbed by the same activity, and increase the domestic inter-sectoral trade, for instance, agriculture could be delivering emissions to forestry and fishing and vice versa if those sectors were separated. The net producers of GHGs in Table 5.5 are primary industries (i.e. agriculture and providers of raw materials), but includes electricity, gas and water supply, and transportation activities as well.

Table 5.6 Sectors classified as net consumers of emissions

		Column 1	Column 2
Reference number		Output - Input (in kt of CO2-eq)	Share of total net-consumed emissions
c3	Food, Beverages and Tobacco	-167 192	49%
c22	Hotels and Restaurants	-31 055	9%
c18	Construction	-27 175	8%
c31	Public Admin and Defence; Compulsory Social Security	-23 176	7%
c33	Health and Social Work	-13 822	4%
c15	Transport Equipment	-12 494	4%
c32	Education	-9 773	3%
c13	Machinery, Nec	-9 011	3%
c30	Renting of M&Eq and Other Business Activities	-6 152	2%
c4	Textiles and Textile Products	-5 928	2%
c14	Electrical and Optical Equipment	-5 726	2%
c28	Financial Intermediation	-5 322	2%
c16	Manufacturing, Nec; Recycling	-4 168	1%
c27	Post and Telecommunications	-3 545	1%
c20	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	-3 077	1%
c21	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	-2 882	1%
c5	Leather, Leather and Footwear	-2 484	1%
c29	Real Estate Activities	-1 887	1%
c7	Pulp, Paper, Paper, Printing and Publishing	-1 859	1%
c8	Coke, Refined Petroleum and Nuclear Fuel	-1 678	0%
c19	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	-781	0%
c9	Chemicals and Chemical Products	-773	0%
c26	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	-639	0%
c6	Wood and Products of Wood and Cork	-163	0%
	Average	-14 198	
	Total GHGs consumed by the above sectors	-340 763	

Net consumers of GHGs were composed mainly of secondary industry activities and service provisions (Table 5.6). This makes sense since these activities absorb emissions embedded in the deliveries of raw materials, electricity, and transportation as inputs for further production to consumers. If we sum the values for Table 5.6 to correspond to the broad sectoral aggregation, services embedded 29% of emissions of domestic inter-sectoral trade, followed by industries (excluding FBT) with 21% and two transportation activities with 1%. Naturally, FBT embedded most of the GHG content with the remaining 49% as a result of a large consumption pattern from agriculture, hunting, forestry and fishing. Table 5.5 and 5.6 show that responsibility for emissions generation in Brazil partially shifts from net producing to net consuming sectors in the total amount of 340 763 kt CO_2-eq. Two sectors stand out, agriculture and FBT for producing almost 70% and consuming almost 50% of GHGs embodied in this domestic inter-sectoral trade, respectively.

Finally, regarding electricity generation, which is a foundational input for all sectors, the electricity, gas and water supply activity was thus a net producer – but not significantly so. The reason for this is perhaps due to the fact that 70% of electricity generation in Brazil came from hydropower in 2008 (Empresa de Pesquisa Energética, 2009). When electricity imports are added – which they are in the above calculations – the share of renewables goes up to 80%, without including the use of biomass burning (Empresa de Pesquisa Energética, 2009). This is in fact much higher than the world average share of renewables in electricity generation, which is approximately 18.5% in 2008 (IEA, 2020). Thus, despite electricity providing inputs to all sectors, its GHGs content in Brazil was not very high, however, its role can be expected to be much more prominent in countries with a higher share of fossil fuels in the energy system.

6 Discussion

6.1 Discussion of results

This work has estimated sectoral footprints for the Brazilian economy during the period 1995-2009 and compared the results obtained with a standard output-based emissions accounting. The first research question was concerned with estimating the footprints of sectors and evaluating the absolute level of pollution of services in relation to other economic activities. The results contradict the idea of services as an environmentally cleaner sector and that structural change could account for the downward slope of the Environmental Kuznets Curve. Proponents of these ideas, as well as of a service transition as a solution for mitigating GHG emissions (Pacala & Socolow, 2004; Panayotou, Peterson & Sachs, 2000; Panayotou, 1993), have only considered the direct impact that services may entail on the environment.

The estimation of input-based emissions, nonetheless, reveal that services are net consumers of emissions, that is, most of the GHGs tied to services are embodied in their input requirements rather than directly produced by them (Larsen & Hertwich, 2009). In this sense, the results reveal that services in Brazil did not happen in isolation to other sectors, but in addition to them, as also outlined by Parrique et al. (2019). This means a service transition is unlikely to reduce output and thus pollution of other sectors, on the contrary, increased service demand will trigger demand for its inputs, such as agricultural production in the case of hotels and restaurants, but from the broad economic structure as in the case of financial intermediation. This is in line with Alcántara and Padilla (2009), where services imposed a strong pull effect on other sectors in Spain, as well as with Suh (2006), which argued a service transition could only benefit the environment if it becomes detached from the production of other industries in the United States.

The emissions from the transportation sector also fall in line with the results obtained by Alcántara and Padilla (2009). In the case of this study, the inclusion of other GHGs in addition to CO_2 has increased the output emission of other sectors in comparison to transportation, which emits mostly CO_2 (Genty, Arto & Neuwahl, 2012). However, when measuring the sector's input emissions, transportation sectors c23, c24 and c25 emerged as a net producers of GHGs. The direct emissions in these transport activities are higher than the emissions embodied in their input requirements. This underpins a sectoral characteristic previously outlined by Alcántara and Padilla (2009) which stressed that an increase in the final demand of several sectors, will lead to an increase in direct transport emissions. This study has confirmed this view by showing that most output emissions from transportation are input requirements to other sectors, and thus, get accounted in other activities' footprint instead. However, the remaining transportation activities (c26 and c27) appeared as net consumers of emissions. This is in fact in agreement with Kander's (2005) proposition of sectoral classification for environmental analysis. Kander (2005) argued that it makes sense to include post and telecommunication activities (c27) under services, despite them being usually classified as transportation. This study confirms such view by showing that post and telecommunications require more emissions than they produce directly as outputs, which is more similar to other service activities (in environmental terms), where transportation emissions should perhaps be viewed as input requirements for their service deliveries.

In relation to previous studies estimating Brazilian emissions, the assessment of sectoral GHG footprints, as well as its comparison with output emissions, contributes to the understanding of responsibility of sectors within the national structure. Machado, Schaeffer and Worrell (2001) concluded that private and public services, as well as textile and clothing products were the least carbon intense activities in the country, whereas in reality, these activities are significant net consumers of emissions and exhibit a substantially higher footprint, and thus responsibility. What Machado, Schaeffer and Worrell (2001) have considered as "textile and clothing" is likely an aggregation of sectors c4 and c5 (i.e. textile and textile products; and leather, leather and footwear) which have had an increase in GHG responsibility of 265% and 702% respectively, which are among the highest increases in the country (Table 5.1).

The estimation of footprints also challenges the perception that emissions in Brazil are highly concentrated in a few sectors as laid out by de Souza, Ribeiro and Perobelli (2016). They are surely not equally distributed, but Figure 5.2 shows that the footprint results reduce the responsibility of agriculture whilst it raises the impact of industries and services, where the three aggregated sectors fluctuate in being slightly under and/or over a quarter of Brazil's emissions. Additionally, it provides the grounds to critique the above authors' estimations that a reduction in output of the main polluting sectors (i.e. livestock and cement production in their case), as a response to climate mitigation targets, would not affect the output of low polluting sectors, especially services (de Souza, Ribeiro & Perobelli, 2016). This conclusion fails to quantify that a drop in agricultural output would significantly affect the provision of inputs to the rest of the economy, likely affecting their output as well.

6.2 Policy implications

The estimation of input-based emissions has shown that the responsibility of sectors for polluting the environment is much more distributed than production estimates show. However, that does not necessarily mean that mitigation policies should attempt to always address all sectors equally. The inter-sectoral dependency through demand and production of GHGs also show that the broad economic structure in Brazil depends on agricultural goods. Thus, by reducing the emissions from agriculture – through improving production techniques and phasing out highly polluting practices, for instance – the impact of FBT, service provisions and other industries will also fall. A change in total production in agriculture will likely affect most of the economic structure in Brazil, but an improvement in the GHG content of its products will naturally reduce the impact of sectors that demand its goods.

Furthermore, this work provides important contributions to the estimation of a national emissions accounting scheme by improving the conditions of monotonicity and sensitivity put forward by Kander et al. (2015). Monotonicity relates to consistency of mitigation strategies, where a reduction in certain region or activities shall not lead to increases in pollution in other places or sectors (Kander et al., 2015). Sensitivity, refers to the characteristics of an emissions indicator in being informative of aspects that countries can control, such as their carbon efficiency and their level of consumption (Kander et al., 2015). It improves the monotonicity aspect by unveiling sectoral interdependencies, where a focus on expanding service provision as means to mitigate GHGs will likely lead to unintended increases in total emissions. The absence of sectoral data can lead to misleading policy targets and undesirable feedbacks. It also contributes to the sensitivity aspect by providing data on the composition of sectoral consumption in Brazil and outlining important and manageable sources of emissions, thus being more receptive to factors that a country can influence.

Additionally, the inclusion of gases such as CH_4 and N_2O provide important policy insights. Firstly, it reveals a much larger and nonnegligible impact of sectors where such gases are present, particularly in agriculture, than when measured purely in CO_2. Secondly, it reveals a significantly higher export impact of Brazil. Taking the year 1995, which is the year for which Machado, Schaeffer and Worrell (2001) have analyzed CO_2 emissions, the total GHGs embodied in exports of the present work have equaled approximately 14% of total GHGs of the Brazilian economy in 1995, which is exactly the same as the CO_2 proportion obtained by Machado, Schaeffer and Worrell (2001). However, the total GHG export content in 1995 was 99 012 kt of CO_2-eq for this work, whereas Machado, Schaeffer and Worrell (2001), measuring only CO_2, have obtained approximately 13 500 kt of CO_2, which is 7 times lower, revealing the importance of including other gases in emissions estimations. The reason for such difference lies in the fact that most of Brazilian exports include agricultural and food industry goods which embed large shares of methane and nitrous oxide in their products (Karstensen, Peters & Andrew, 2013; Zaks et al., 2009).

Finally, another important aspect to be noted is that this work has assigned responsibility for pollution to the productive sectors of the economy. Thus, the total pollution of sectors was estimated to serve the aggregated final demand in Brazil. However, when the total national values are split between final demand categories, *final consumption expenditure by household* was the main force driving production in Brazil. In 2008 households were responsible for consuming 522 002 kt of CO_2-eq, including imports, which is roughly 75% of national CBA emissions. In addition, *exports* for final demand were also a significant driver of GHGs, in 2008 at the value of 223 845 kt of CO_2-eq. However, these emissions are also largely due to the demand of individual consumers at the importing countries, therefore, highlighting that it is through people's personal consumption that most of the emission are driven throughout the economy.

7 Conclusion

7.1 Concluding remarks

This paper has provided the first estimates of sectoral GHG footprints for the Brazilian economy, using data for the period 1995-2009. It has compared the results to a standard production measure of emissions for each sector, which were referred to in this paper as output-based emissions. The footprint estimation has provided a novel contribution to the calculation of GHG responsibility of sectors for Brazil through allocating the burden of emissions into the parties that have consumed and demanded it. It further proposed the grouping of sectors between net producers and net consumers of emissions, based on the difference between their output-based and footprint indicators. This classification aimed to contribute to the understanding of sectoral interdependencies by unveiling the responsibility of all sectors in being producers and/or demanders of pollution. This paper has done so by addressing the questions:

(1) *What were the GHG footprints of the productive sectors in Brazil throughout the period 1995-2009?*
   a. *Can the service sector still be regarded as less polluting than others in absolute terms when its complete footprint is taken into account?*

(2) *Comparing the original output-based estimates with the actual footprint of economic activities, which sectors emerge as net producers and net consumers of emissions?*
   a. *Does emission responsibility of sectors change under such classification?*

This paper concludes that the greenhouse gas footprints for each disaggregated sector were found to be significantly different than their output-based estimates for which they are commonly assigned to. The variation between sectors naturally differs, with some sectors experiencing less of a change than others. Food, beverages and tobacco; hotels and restaurants; and financial intermediation emerged with the largest percentage increase between indicators, that is, 3461%, 1829% and 1091% increase, respectively. In absolute terms, other sectors stood out, such as agriculture, where over half of its output emissions (which equals 33% of the national total) became assigned to other activities' footprints instead. In this process, the values for the broad sectoral aggregation were presented, where the aggregate services could not be considered less polluting than other activities, since the GHGs embodied in its consumption were similar to the agriculture's footprint and higher than the aggregate industries (excluding food, beverages and tobacco).

All sectors with an output emission higher than its footprint, were classified as net producers of emissions, and net consumers were activities exhibiting a higher footprint than an output-based value. Industries were characterized by a heterogenous result with certain sectors emerging as significant net consumers, such as FBT and transport equipment, and others as large net producers of emissions, as in the case of mining and quarrying, and other non-metallic mineral. Services were largely net consumers of GHGs, most of their pollution was embodied in their consumption, rather than through their service delivery. Agriculture was a net producer of emissions, where over half of GHGs emitted were in fact demanded by other sectors across the economy. And finally, transportation activities emerged as net producers; a larger share of emissions generated in this sector were demanded by other activities, rather than to serve its own final demand. Therefore, the estimations performed in this work allocated part of the burden of pollution to the activities that demanded its generation representing a transfer of emissions from net producers to net consumers, which resulted in a different distribution of sectoral pollution and a significant change in the GHG responsibility of sectors.

7.2 Limitations and areas for future study

Despite the robust methodology applied and the detailed processing of data, the present study suffers of deficiencies worthy of consideration. First, it does not include emissions from Land Use Change and Forestry (LUCF) activities, such as deforestation and soil burning. LUCF are not defined as a productive sector of the economy and their impact is not included in Input-Output tables, thus their consideration would need the employment of a different methodological approach, which could hamper the estimations of inter-sectoral emissions, for which IO tables are well suited to use. For this reason, they were not included in this study. However, they remain an important source of emissions in Brazil, and their inclusion would likely increase the footprint of the food industry and the impact of the country's exports (de Souza, Ribeiro & Perobelli, 2016; Karstensen, Peters & Andrew, 2013; Cerri et al., 2009; Zaks et al., 2009). Second, the estimation of import emissions assumes that goods were produced using the same technology level for all countries. Accounting for technological differences is particularly pertinent to studies analyzing international trade since it affects the responsibility of countries in cleaning up their export industries. But it can naturally affect sectoral footprints, and thus should be accounted. This was not performed in this study, because providing detailed sectoral data adjusted for technology would require analyzing the detailed sector flows of all countries to Brazil, which would have demanded a significant amount of time.

Third, the dataset used contain values for 1995-2009 which may prove to be outdated for some aspects if more recent years are analyzed. Fourth, the estimation of input-based emissions followed most studies in footprints by allocating full responsibility to the consuming party, however, this can perhaps be suboptimal. Estimating emissions on a shared responsibility basis can lead to improved insights for policy formulation and mitigation strategies. Some studies have assigned a 50-50 responsibility burden to producers and consumers (e.g. Zaks et al., 2009), and others have split the results between final demand categories and assigned responsibility to direct final household consumption (e.g. Lenzen & Murray, 2001). Fifth, the estimation of GHG footprints was analyzed under an absolute content rather than their intensity (i.e. GHGs per dollar of output). Intensity measures can be useful to adjust the level of pollution of an activity by its respective size and contribution to economic output. However, IO tables provide monetary value flows in current prices, which has been shown to lead to a bigger size of the service sector than they actually are in comparison to other activities (Henriques & Kander, 2010; Kander, 2005), thus likely influencing the results to show a lower service footprint intensity than would be found in constant prices.

Therefore, possible paths for future research include addressing some of the limitations described above, such as including LUCF emissions, and converting IO tables to constant price values to appropriately measure sectoral intensity indicators. However, it also includes expanding the first sectoral footprint estimates laid out in this work by including a more disaggregated sectoral definition. It was found that the food, beverages, and tobacco sector have a very large footprint, but the exact activities within this sector that are responsible for such consumption can only be speculated here to be beef and soy production based on previous studies (de Souza, Ribeiro & Perobelli, 2016; Karstensen, Peters & Andrew, 2013; Zaks et al., 2009). In addition, the sectoral footprint analysis can be expanded to address other countries as well as to estimate the responsibility of sectors within international trade, where adjustments for technological differences between countries would contribute to the analysis.

References

Alcántara, V. & Padilla, E. (2009). Input–Output Subsystems and Pollution: An Application to the Service Sector and CO2 Emissions in Spain, *Ecological Economics*, vol. 68, no. 3, pp.905–914.

Baumert, N., Kander, A., Jiborn, M., Kulionis, V. & Nielsen, T. (2019). Global Outsourcing of Carbon Emissions 1995–2009: A Reassessment, *Environmental Science & Policy*, vol. 92, pp.228–236.

Bicknell, K. B., Ball, R. J., Cullen, R. & Bigsby, H. R. (1998). New Methodology for the Ecological Footprint with an Application to the New Zealand Economy, *Ecological Economics*, vol. 27, no. 2, pp.149–160.

Cerri, C. C., Maia, S. M. F., Galdos, M. V., Cerri, C. E. P., Feigl, B. J. & Bernoux, M. (2009). Brazilian Greenhouse Gas Emissions: The Importance of Agriculture and Livestock, *Scientia Agricola*, vol. 66, no. 6, pp.831–843.

Davis, S. J. & Caldeira, K. (2010). Consumption-Based Accounting of CO2 Emissions, *Proceedings of the National Academy of Sciences*, vol. 107, no. 12, pp.5687–5692.

de Azevedo, T. R., Costa Junior, C., Brandão Junior, A., Cremer, M. dos S., Piatto, M., Tsai, D. S., Barreto, P., Martins, H., Sales, M., Galuchi, T., Rodrigues, A., Morgado, R., Ferreira, A. L., Barcellos e Silva, F., Viscondi, G. de F., dos Santos, K. C., Cunha, K. B. da, Manetti, A., Coluna, I. M. E., Albuquerque, I. R. de, Junior, S. W., Leite, C. & Kishinami, R. (2018). SEEG Initiative Estimates of Brazilian Greenhouse Gas Emissions from 1970 to 2015, *Scientific Data*, vol. 5, no. 1, p.180045.

de Jesus Teixeira, M. D., Nogueira, J. M., Imbroisi, D. & de Melo Faria, A. M. (2020). Strategic Sectors for Greenhouse Gas Mitigation Investment: Assessment Based upon the Brazil's Input-Output Matrix, *Mitigation and Adaptation Strategies for Global Change*, vol. 25, no. 2, pp.261–283.

de Souza, K. B., Ribeiro, L. C. de S. & Perobelli, F. S. (2016). Reducing Brazilian Greenhouse Gas Emissions: Scenario Simulations of Targets and Policies, *Economic Systems Research*, vol. 28, no. 4, pp.482–496.

Dinda, S. (2004). Environmental Kuznets Curve Hypothesis: A Survey, *Ecological Economics*, vol. 49, no. 4, pp.431–455.

Empresa de Pesquisa Energética. (2009). Balanço Energético Nacional 2009: Ano base 2008, Rio de Janeiro: EPE

Ferng, J.-J. (2001). Using Composition of Land Multiplier to Estimate Ecological Footprints Associated with Production Activity, *Ecological Economics*, vol. 37, no. 2, pp.159–172.

Genty, A., Arto, I. & Neuwahl, F. (2012). Final Database of Environmental Satellite Accounts: Technical Report on Their Compilation, *WIOD deliverable*, vol. 4, no. 6.

Grossman, G. & Krueger, A. (1991). Environmental Impacts of a North American Free Trade Agreement, w3914, Cambridge, MA: National Bureau of Economic Research, p.w3914, Available Online: http://www.nber.org/papers/w3914.pdf [Accessed 31 May 2020].

Grossman, G. M. & Krueger, A. B. (1995). Economic Growth and the Environment, *The quarterly journal of economics*, vol. 110, no. 2, pp.353–377.

Henriques, S. T. & Kander, A. (2010). The Modest Environmental Relief Resulting from the Transition to a Service Economy, *Ecological Economics*, vol. 70, no. 2, pp.271–282.

IEA. (2020). Data Tables – Data & Statistics, *IEA*, Available Online: https://www.iea.org/data-and-statistics/data-tables [Accessed 14 June 2020].

ILOSTAT. (2020). International Standard Industrial Classification of All Economic Activities (ISIC), *ILOSTAT*, Available Online: https://ilostat.ilo.org/resources/methods/classification-economic-activities/ [Accessed 11 May 2020].

International Standard Industrial Classification of All Economic Activities (ISIC) United Nations (1990) Revision 3, Series M: Miscellaneous Statistical Papers, No. 4 Rev. 3, New York, Available online: https://unstats.un.org/unsd/classifications/Econ/Download/In%20Text/ISIC_Rev_3_English.pdf [Accessed 11 May 2020]

IPCC. (2013). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (Eds.)], *Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA*, p.1535.

IPCC, C. C. (2007). The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (Eds.)], *Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA*, vol. 996, p.2007.

Kaika, D. & Zervas, E. (2013). The Environmental Kuznets Curve (EKC) Theory—Part A: Concept, Causes and the CO2 Emissions Case, *Energy Policy*, vol. 62, pp.1392–1402.

Kander, A. (2005). Baumol’s Disease and Dematerialization of the Economy, *Ecological Economics*, vol. 55, no. 1, pp.119–130.

Kander, A., Jiborn, M., Moran, D. D. & Wiedmann, T. O. (2015). National Greenhouse-Gas Accounting for Effective Climate Policy on International Trade, *Nature Climate Change*, vol. 5, no. 5, pp.431–435.

Karstensen, J., Peters, G. P. & Andrew, R. M. (2013). Attribution of CO2 Emissions from Brazilian Deforestation to Consumers between 1990 and 2010, *Environmental Research Letters*, vol. 8, no. 2, p.024005.

Kuznets, S. (1955). Economic Growth and Income Inequality, *The American economic review*, vol. 45, no. 1, pp.1–28.

Larsen, H. N. & Hertwich, E. G. (2009). The Case for Consumption-Based Accounting of Greenhouse Gas Emissions to Promote Local Climate Action, *Environmental Science & Policy*, vol. 12, no. 7, pp.791–798.

Lenzen, M. (1998). Primary Energy and Greenhouse Gases Embodied in Australian Final Consumption: An Input–Output Analysis, *Energy Policy*, vol. 26, no. 6, pp.495–506.

Lenzen, M. (2001). A Generalized Input-Output Multiplier Calculus for Australia, *Economic Systems Research*, vol. 13, no. 1, pp.65–92.

Lenzen, M. & Murray, S. A. (2001). A Modified Ecological Footprint Method and Its Application to Australia, *Ecological Economics*, vol. 37, no. 2, pp.229–255.

Lenzen, M., Pade, L.-L. & Munksgaard, J. (2004). CO2 Multipliers in Multi-Region Input-Output Models, *Economic Systems Research*, vol. 16, no. 4, pp.391–412.

Leontief, W. (1970). Environmental Repercussions and the Economic Structure: An Input-Output Approach, *The review of economics and statistics*, pp.262–271.

Leontief, W. W. (1936). Quantitative Input and Output Relations in the Economic Systems of the United States, *The review of economic statistics*, pp.105–125.

Machado, G., Schaeffer, R. & Worrell, E. (2001). Energy and Carbon Embodied in the International Trade of Brazil: An Input–Output Approach, *Ecological Economics*, vol. 39, no. 3, pp.409–424.

Minx, J. C., Wiedmann, T., Wood, R., Peters, G. P., Lenzen, M., Owen, A., Scott, K., Barrett, J., Hubacek, K., Baiocchi, G., Paul, A., Dawkins, E., Briggs, J., Guan, D., Suh, S. & Ackerman, F. (2009). INPUT–OUTPUT ANALYSIS AND CARBON FOOTPRINTING: AN OVERVIEW OF APPLICATIONS, *Economic Systems Research*, vol. 21, no. 3, pp.187–216.

OECD. (2020). Air and GHG Emissions [indicator], Available Online: https://www.oecd-ilibrary.org/environment/air-and-ghg-emissions/indicator/english_93d10cf7-en [Accessed 10 June 2020].

Pacala, S. & Socolow, R. (2004). Stabilization Wedges: Solving the Climate Problem for the next 50 Years with Current Technologies, *science*, vol. 305, no. 5686, pp.968–972.

Panayotou, T. (1993). Empirical Tests and Policy Analysis of Environmental Degradation at Different Stages of Economic Development, International Labour Organization.

Panayotou, T., Peterson, A. & Sachs, J. D. (2000). Is the Environmental Kuznets Curve Driven by Structural Change? What Extended Time Series May Imply for Developing Countries.

Parrique, T., Barth, J., Briens, F., Kerschner, C., Kraus-Polk, A., Kuokkanen, A. & Spangenberg, J. H. (2019). Decoupling Debunked, *Evidence and arguments against green growth as a sole strategy for sustainability. A study edited by the European Environment Bureau EEB*.

Peters, G. P. & Hertwich, E. G. (2008). Post-Kyoto Greenhouse Gas Inventories: Production versus Consumption, *Climatic Change*, vol. 86, no. 1–2, pp.51–66.

Peters, G. P., Minx, J. C., Weber, C. L. & Edenhofer, O. (2011). Growth in Emission Transfers via International Trade from 1990 to 2008, *Proceedings of the National Academy of Sciences*, vol. 108, no. 21, pp.8903–8908.

Schaeffer, R. & de Sá, A. (1996). The Embodiment of Carbon Associated with Brazilian Imports and Exports, *Energy Conversion and Management*, vol. 37, no. 6–8, pp.955–960.

Stern, D. I. (2004). The Rise and Fall of the Environmental Kuznets Curve, *World Development*, vol. 32, no. 8, pp.1419–1439.

Suh, S. (2006). Are Services Better for Climate Change?, *Environmental Science & Technology*, vol. 40, no. 21, pp.6555–6560.

Tarancón Morán, M. Á. & del Río González, P. (2007). A Combined Input–Output and Sensitivity Analysis Approach to Analyse Sector Linkages and CO2 Emissions, *Energy Economics*, vol. 29, no. 3, pp.578–597.

Timmer, M. P., Dietzenbacher, E., Los, B., Stehrer, R. & Vries, G. J. de. (2015). An Illustrated User Guide to the World Input–Output Database: The Case of Global Automotive Production, *Review of International Economics*, vol. 23, no. 3, pp.575–605.

US EPA, O. (2016). Understanding Global Warming Potentials [Overviews and Factsheets], *US EPA*, Available Online: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials [Accessed 24 May 2020].

Wiedmann, T., Minx, J., Barrett, J. & Wackernagel, M. (2006). Allocating Ecological Footprints to Final Consumption Categories with Input–Output Analysis, *Ecological Economics*, vol. 56, no. 1, pp.28–48.

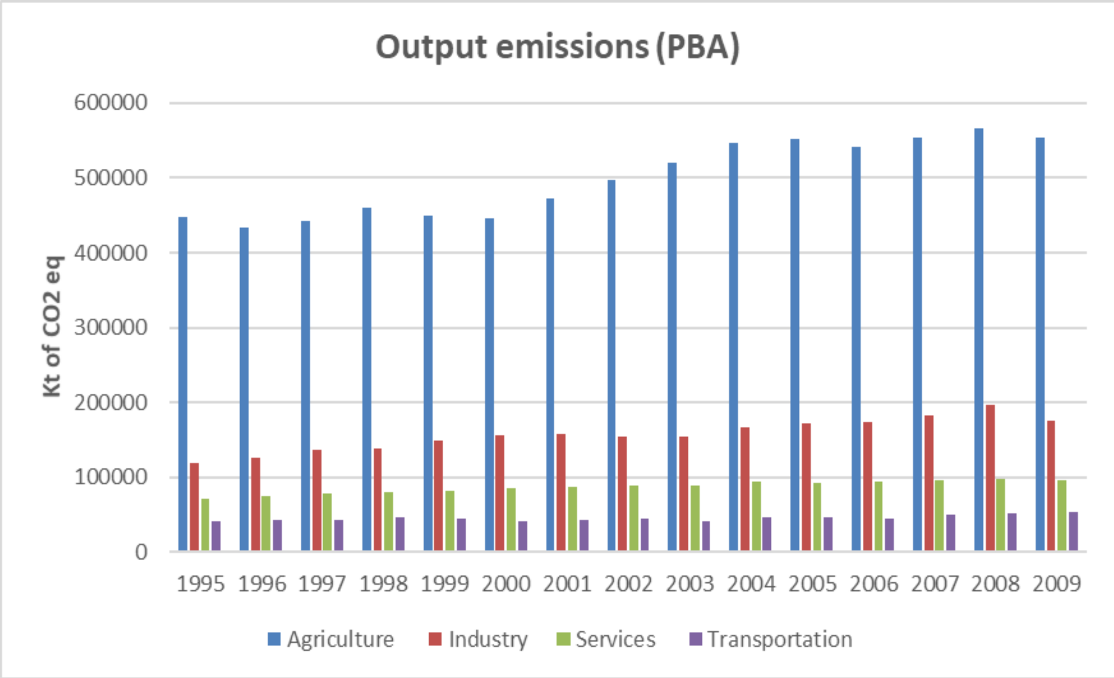
Zaks, D. P. M., Barford, C. C., Ramankutty, N. & Foley, J. A. (2009). Producer and Consumer Responsibility for Greenhouse Gas Emissions from Agricultural Production—a Perspective from the Brazilian Amazon, *Environmental Research Letters*, vol. 4, no. 4, p.044010.

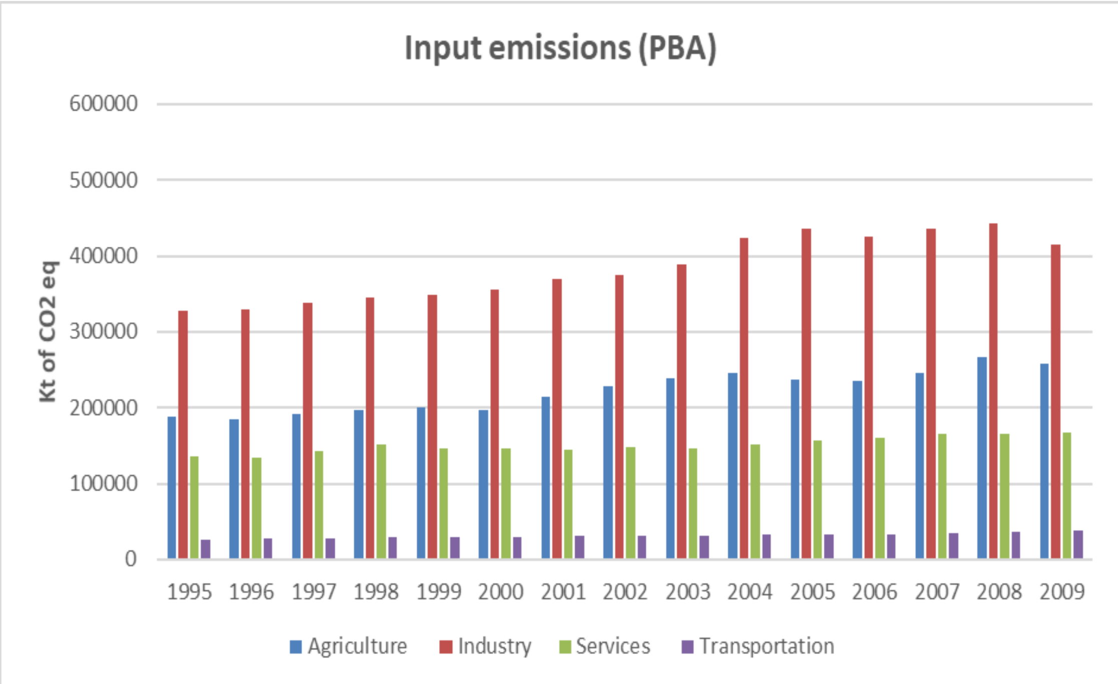
Appendix A

Appendix A 1. PBA results for output emissions; emissions footprint and their percentage difference for all sectors in 2008

		GHG emissions (Output-based) in kt of CO2-eq		GHG footprints (Input-based) in kt of CO2-eq		% Δ
c1	Agriculture, Hunting, Forestry and Fishing	566 193		267 460		-53%
c2	Mining and Quarrying	40 963		19 605		-52%
c3	Food, Beverages and Tobacco	6 193		232 741		3658%
c4	Textiles and Textile Products	2 408		8 839		267%
c5	Leather, Leather and Footwear	479		4 051		745%
c6	Wood and Products of Wood and Cork	487		2 335		380%
c7	Pulp, Paper, Paper, Printing and Publishing	4 494		8 342		86%
c8	Coke, Refined Petroleum and Nuclear Fuel	24 088		29 375		22%
c9	Chemicals and Chemical Products	19 960		21 028		5%
c10	Rubber and Plastics	1 178		1 454		23%
c11	Other Non-Metallic Mineral	25 221		4 707		-81%
c12	Basic Metals and Fabricated Metal	34 304		20 788		-39%
c13	Machinery, Nec	1 245		12 216		881%
c14	Electrical and Optical Equipment	1 816		8 679		378%
c15	Transport Equipment	1 479		18 845		1175%
c16	Manufacturing, Nec; Recycling	769		5 278		587%
c17	Electricity, Gas and Water Supply	27 579		13 790		-50%
c18	Construction	3 983		31 313		686%
c19	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	815		1 530		88%
c20	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	1 390		4 376		215%
c21	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	6 109		8 464		39%
c22	Hotels and Restaurants	1 848		37 174		1912%
c23	Inland Transport	36 205		21 163		-42%
c24	Water Transport	7 605		3 526		-54%
c25	Air Transport	2 155		1 441		-33%
c26	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	3 923		4 479		14%
c27	Post and Telecommunications	2 486		6 277		152%
c28	Financial Intermediation	532		5 922		1014%
c29	Real Estate Activities	364		2 269		524%
c30	Renting of M&Eq and Other Business Activities	4 959		11 517		132%
c31	Public Admin and Defence; Compulsory Social Security	8 031		31 229		289%
c32	Education	2 696		12 472		363%
c33	Health and Social Work	1 864		15 693		742%
c34	Other Community, Social and Personal Services	68 570		34 011		-50%
	Total	912 391		912 391		

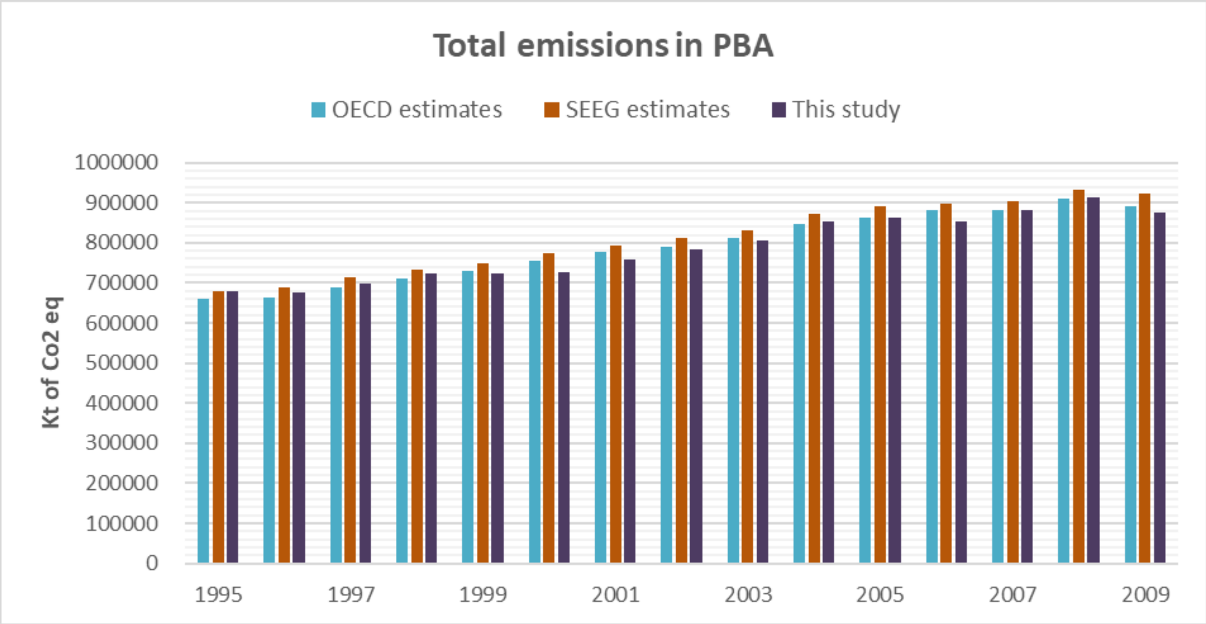
Appendix A 2. GHG emissions under a broad sectoral aggregation in output and input indicators (1995-2009) under a PBA national value





Appendix B

Appendix B 1. PBA results compared to other study estimates



Source: own construction based on OECD (2020) and de Azevedo et al. (2018).

Note: The values used in the Figure above refer to the PBA estimates of this study. The OECD and the SEEG values were chosen due to their comparability with this study by measuring in GHGs (de Azevedo et al., 2018; OECD, 2020). Slight differences between the three indicators are due to different methodologies applied and the inclusion of more gases by both official estimates.

Appendix C

Appendix C 1. Broad sectoral concordance with ISIC rev.3.

Agriculture	Agriculture, Hunting, Forestry and Fishing	c1
Industry	Mining and Quarrying	c2
	Food, Beverages and Tobacco	c3
	Textiles and Textile Products	c4
	Leather, Leather and Footwear	c5
	Wood and Products of Wood and Cork	c6
	Pulp, Paper, Paper, Printing and Publishing	c7
	Coke, Refined Petroleum and Nuclear Fuel	c8
	Chemicals and Chemical Products	c9
	Rubber and Plastics	c10
	Other Non-Metallic Mineral	c11
	Basic Metals and Fabricated Metal	c12
	Machinery, Nec	c13
	Electrical and Optical Equipment	c14
	Transport Equipment	c15
	Manufacturing, Nec; Recycling	c16
	Electricity, Gas and Water Supply	c17
	Construction	c18
Services	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	c19
	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	c20
	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	c21
	Hotels and Restaurants	c22
Transportation	Inland Transport	c23
	Water Transport	c24
	Air Transport	c25
	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	c26
	Post and Telecommunications	c27
Services	Financial Intermediation	c28
	Real Estate Activities	c29
	Renting of M&Eq and Other Business Activities	c30
	Public Admin and Defence; Compulsory Social Security	c31
	Education	c32
	Health and Social Work	c33
	Other Community, Social and Personal Services	c34

Source: Own construction based on International Labour Organization (ILOSTAT, 2020) and Kander (2005). The split of Transportation from Services followed ISIC rev.3 definition of Transportation.