Tracing Brazilian regions' CO2 emissions in domestic and global trade

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Abstract:

The current Brazilian position on climate change has been formalized with the law of National Climate Change Policy, which provides a legal framework for national actions aimed at mitigation and adaptation. Within PNMC, the country has defined its national voluntary reduction targets for greenhouse gases emissions, with reductions between 36.1% and 38.9% of projected emissions by 2020. The distribution of the corresponding mitigation efforts by regions is of great concern in a large country like Brazil. In fact, most of Brazilian states have established public policies on climate change. In this context, questions raised in the literature on global climate change, such as the environmental responsibility for emissions embodied in trade, also apply at the regional level, and perhaps even to a larger extent. In order to analyze at regional level the current relationship between Brazil's CO2 emissions and domestic and global value chains, in this study we adopt a new framework that combines a world input-output table with an inter-regional input-output table. Also, a new database is compiled on Brazilian states' energy use (by fuel) and related CO2 emissions at sectoral level, based on states' official energy balances. We are able to evaluate the CO2 emissions in each of the 27 Brazilian states, considering their respective productive structure, energy use, as well as their trade with other states or foreign countries. We find that, in 2008, emissions from the production of inter-regionally traded goods and services corresponded to 36% of Brazilian CO2 emissions. There is great variation among states concerning their emissions intensities and carbon content of their trade relationships with their states and foreign countries.

Keywords: CO2 emissions, input-output analysis, global value chains

JEL Codes: Q56, C67, R15

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1. Introduction

The Brazilian position on climate change was formalized by the National Climate Change Policy (PNMC, in Portuguese – Law nº 12 187, dated December 29, 2009), which provides a legal framework for national actions aimed at mitigation and adaptation. The PNMC defines the country's national voluntary reduction targets for greenhouse gas (GHG) emissions advancing the policy from merely programmatic (LUCON; GOLDEMBERG, 2010) to a legal commitment with clear environmental objectives that should guide subsequent policymaking. The reduction targets were defined as between 36.1% and 38.9% of projected emissions by 2020. Seroa da Motta (2011) indicated that sectoral mitigation percentages were adopted in the correspondence from Brazil for the Copenhagen Accord in 2010: of the 38.9% national target, deforestation would be responsible for 24.7%, and the remaining 15.2% would be allocated to energy use (7.7%), agriculture and cattle raising (6.1%), and other sectors (0.4%).

Minimal focus is on the distribution of the corresponding mitigation efforts by regions. This is of great concern in a large country such as Brazil with substantial regional variation in economic development, physical geography, production systems, and energy consumption. Brazil's 1988 Constitution divides the responsibilities for environmental policies and legislation among the three levels of government (PUPPIM DE OLIVEIRA, 2009), and most Brazilian states have established public policies on climate change. According to NESA-USP, as of September 2015, of the 27 states, 16 have established policies and four are underway having initiated draft legislation; three others have implemented local forums to discuss climate change at the state level. Only Roraima in the North region, and Alagoas, Rio Grande do Norte, and Sergipe in the Northeast region do have climate change forums. Figure 1 shows the configuration of climate policies in Brazilian states as of September 2015.

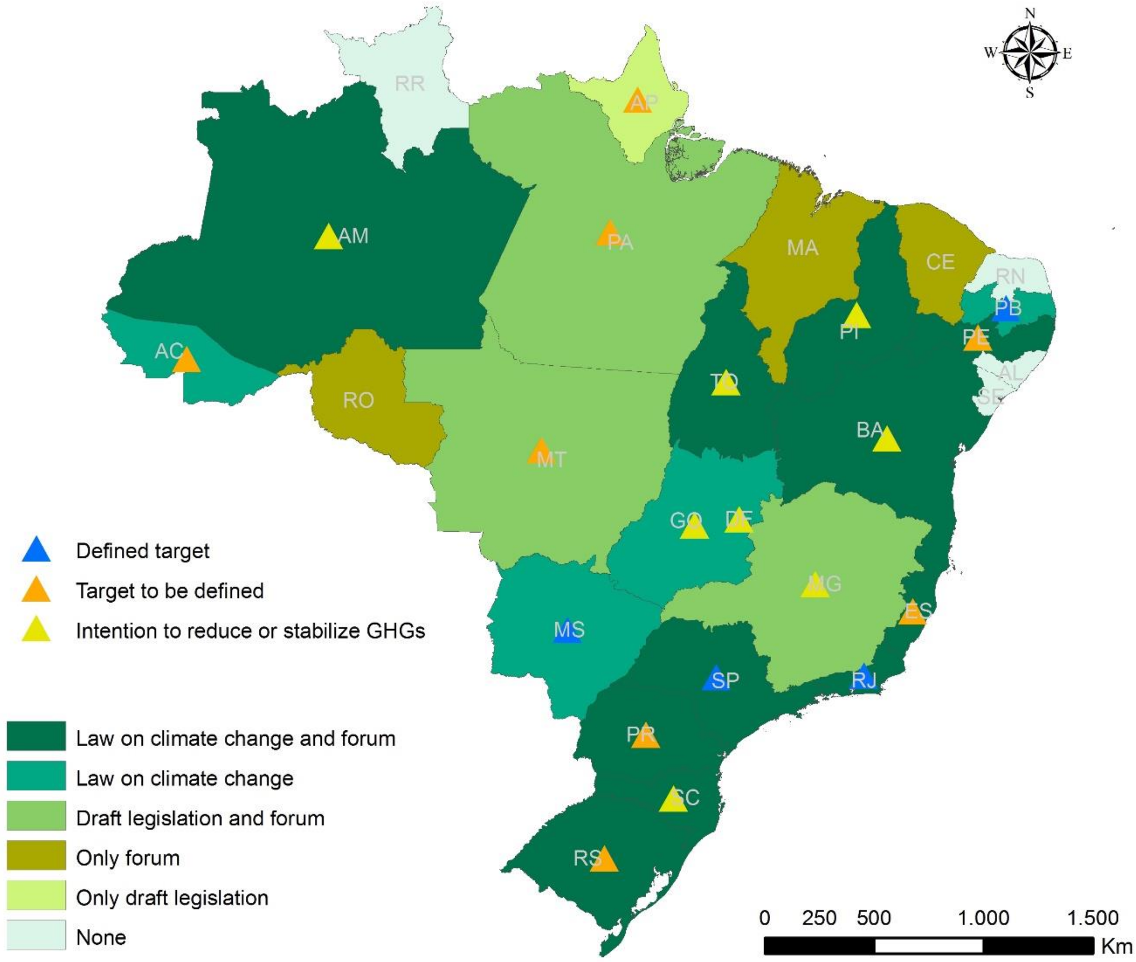

Figure 1 – Brazilian states' climate change policies, September 2015

Source: NESA (2015). Prepared by the author.

Four states have mandatory targets for reducing GHG emissions: São Paulo and Rio de Janeiro in the most developed Southeast region; Mato Grosso do Sul in the Central-West region, and Paraíba, in the Northeast region. There are also advancements in municipal climate change policies. The two most populous cities in Brazil, São Paulo and Rio de Janeiro, have established mandatory targets. The chart below summarizes the targets established by federal, state, and municipal laws related to climate change.

Chart 1 – Subnational policies with mandatory targets for reducing greenhouse gas emissions

Government level	Policy	Law	Targets	Baseline
Federal	National Policy on Climate Change	nº 12 187 / 2009	36.1% and 38.9%	Projected emissions by 2020
State	State Policy on Climate Change of São Paulo	nº 13 798 / 2009	20% by 2020	Based on the inventory of 2005
	State Policy on Climate Change of Rio de Janeiro	Decreto nº 43 216 / 2011	Reducing emissions intensity (tCO_2e / GDP) by 2030	Based on the inventory of 2005
	State Policy on Climate Change of Paraíba	nº 9 336 / 2011	36.1% and 38.9%	Projected emissions by 2020
	State Policy on Climate Change of Mato Grosso do Sul	nº 4.555 / 2014	20% by 2020	Based on the inventory 2005
Municipal	Municipal Policy on Climate Change of São Paulo	nº 14 933 / 2009	30% by 2012	Based on the inventory of 2005
	Municipal Policy on Climate Change of Rio de Janeiro	nº 5.248 / 2011	8% by 2012, 16% by 2016, 20% by 2020	Based on the inventory of 2005

Source: Romeiro; Parente (2011); NESA (2015). Prepared by the author.

The chart shows that the mitigation targets for Brazil's subnational climate change policies differ significantly. This is not a problem in itself and can be echoing the principle of "common but differentiated responsibilities" professed by PNMC at the international level. However, there is no coordination concerning the measurement basis (absolute values or intensities in the case of Rio de Janeiro), and there are incompatibilities in the baselines (different years of reference based on inventories or projected emissions). At the sectoral level, only Rio de Janeiro has stated specific targets.

These characteristics reflect that the subnational policy elaboration processes, which have autonomously emerged, are detached from one other. The incongruity between the targets is problematic for economic agents because the implications of national, state, and municipal policies are unclear (FORUM CLIMA, 2012). Thus, although the subnational policies indicate advances toward a less intensive effect on climate change, the regulatory aspects require improvement. Romeiro and Parente (2011) stated that the lack of convergence in actions increases the difficulty and reduces the effectiveness of the mitigation measures and the respective monitoring.

This criticism is not exclusive to Brazil but is applied to other countries where subnational climate policies have emerged. Literature concerning these policies has flourished in recent years, and subnational governments have led climate change efforts in many countries such as the USA (LUTSEY; SPERLING, 2008; SCHREURS, 2008). Although there are advantages associated with the engagement of subnational governments in climate change policies – such as greater flexibility in implementing new policies (PUPPIM DE OLIVEIRA, 2009) and efficiency gains from the exploitation of local heterogeneities (SOMANATHAN *et al*, 2014) – most literature agrees that the possibility of coordination and complementarity problems exist and questions institutional capacity to take action on such policies. The Intergovernmental Panel on Climate Change's Fifth Assessment Report states that because there are several limiting factors to widespread reliance on subnational levels of government, "a federal structure that provides coordination and enables an easier transmission of climate policies throughout the agents of the economy is likely to increase the effectiveness of actions against climate change" (SOMANATHAN *et al*, 2014, p. 1183).

The coordination of top-down policies is also fundamental in addressing an important aspect of climate change that has been overlooked by policy settings at all levels, which is the driving force of consumption patterns and, consequently, the relationship between trade and GHG emissions. Human-induced climate change is a global externality from production activities (STERN, 2008), and its assessment must consider the connections between economies as trade links for production and consumption in different regions. Peters *et al* (2011) stated that ignoring these connections might result in a misleading analysis of the underlying driving forces of emission trends and lead to suboptimal mitigation policies.

Hoekstra and Wiedmann (2014) indicated that the Kyoto Protocol is an example of a well-intended but ineffective policy. The Protocol adopts a fragmented, two-tier mitigation strategy; it sets reduction targets per Annex B countries with respect to GHG emissions within the territory while the developing countries do not have emission commitments. In this setting, concern for carbon leakage (i.e., increasing CO_2 emissions in countries outside of the agreement's control) arises.[1] Peters *et al* (2011) found that global CO_2 emissions have grown 39% from 1990 to 2008. While emissions in developed countries have stabilized, emissions in developing countries have doubled. In the same period, the net emission transfers from non-Annex B to Annex B countries has grown 17% per year on average.[2] While it is not clear if these increasing flows are caused by climate policy itself (i.e., whether they represent "strong carbon leakage" or "weak carbon leakage"), given the dynamics of the world economy, the increasing flows are sufficient to cause substantial concern for the effectiveness of climate regimes with limited participation (PETERS; HERTWICH, 2008).

The current framework of subnational climate policies in Brazil suggests concern for carbon leakage within the country because the interrelationships between the states are disregarded. For example, São Paulo, whose industries present low average emission intensities (as we will see in the following), is one of the few states with established mitigation targets. To meet the commitment, the state could shift emissions to other regions in the country so that national emissions might not reduce or increase with regional leakage. Therefore, assessing the interregional flows of CO_2 emissions within the country is, thus, essential for effective mitigation strategies.

Therefore, the questions raised in the literature concerning the emissions embodied in international trade, particularly the environmental responsibility for those emissions (e.g., VALE *et al*, 2015; DOUGLAS; NISHIOKA, 2012; WIEBE *et al*, 2012; PETERS *et al*, 2011; DAVIS; CALDEIRA, 2010; NAKANO *et al*, 2010; SERRANO; DIETZENBACHER, 2010; PETERS; HERTWICH, 2009), also apply at the regional level. To add to the understanding of the relationship between subnational regional trade and their emissions, this paper quantifies the CO_2 emissions embodied in Brazilian states' trade. We adopt a forward perspective (MENG *et al*, 2015) in the analysis. That is, we aim to understand the responsibility of consumers for emissions embodied in trade, evaluating the amount of emission generated by a state that is for

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[1] According to Peters and Hertwich (2008), increased carbon leakage can be caused by two factors. First, in response to mitigation policy, production migrates in the direction of non-participating countries with lax environmental regulations ("strong carbon leakage"). Second, regardless of climate policies, increased consumption in a participating country is met by increased production in a non-participating country ("weak carbon leakage").

[2] Peter *et al* (2011) adopted the "emissions embodied in bilateral trade (EEBT)" from Peters (2008) and defined net emission transfers as "CO2 emissions in each country to produce exported goods and services minus the emissions in other countries to produce imported goods and services." In our paper, we apply a methodology close to Peters' (2008) approach based on a multi-regional input-output analysis (MRIO) and define net emission transfers as CO2 emissions in each country to produce goods and services that are ultimately consumed abroad minus the emissions in other countries to produce goods and services that are ultimately consumed in the country.

its own final consumption and the amount of emission generated for consumption by other states and foreign countries.

Recognizing the significance of intersectoral linkages is fundamental. Thus, the IO methodology is an appropriate tool to investigate environmental impacts considering the links between the various sectors and regions of an economy. Moreover, given the increasing interconnectedness of domestic and global production processes, CO_2 emissions embodied in trade in the context of GVCs are significant even if the focus is on domestic regions (PEI *et al*, 2015). For Brazil, studies that analyze sectoral GHG emissions at the subnational level have been developed by applying either single-region (e.g., CARVALHO *et al*, 2013) or interregional IO models (e.g., IMORI *et al*, 2015; CASTELANI, 2014; CARVALHO; PEROBELLI, 2009; HILGEMBERG; GUILHOTO, 2006). A frequent concern of these studies, the effect of emissions exports, was addressed by impact analysis of exogenous variations in the final demand vectors. Our study goes further by applying a full country-state IO table to comprehend endogenously the world economy using the 27 Brazilian states as distinct regions. Chapter 2 describes the estimation procedure.

Our approach is comparable to Feng *et al* (2013) and Pei *et al* (2015), who studied the CO_2 emissions embodied in trade for Chinese regions. Feng *et al* (2013) used GTAP-MRIO data and split China into 30 sub-regions (26 provinces and four cities) while Pei *et al* (2015) applied the model developed by Meng *et al* (2013), which used WIOD data and split China into four regions. Both studies found a clear pattern for interregional trade in CO_2 emissions: highly developed coastal regions of China are large net takers of CO_2 emissions from less developed inland regions. Concerning the participation in GVCs, Pei *et al* (2015) observed that the inland regions were indirectly involved in GVCs by providing high carbon intensity inputs to downstream and exporting coastal regions. A central implication from the observed trade pattern is that because China's climate policy seeks to address regional differences by setting higher mitigation targets for coastal regions, this may cause additional outsourcing and carbon leakage in the direction of less developed regions. In our study, we analyze if the interdependence of Brazilian states with respect to CO_2 emissions shows a clear pattern similar to that of Chinese provinces.

A major difficulty for subnational climate change policies in Brazil is the limited published official inventories (although state policies typically urge their formulation). At the state level, to the best of our knowledge, only Espírito Santo, Minas Gerais, Paraná, Rio de Janeiro, and São Paulo have published comprehensive GHG inventories.[3] Inventory periodicity differs, and the adopted methodologies are not entirely consistent. For example, proposals for accounting for emissions from freight originating in the state with an out-of-state destination are inconsistent (FORUM CLIMA, 2012). To address this problem, we quantify CO_2 emissions in each of the 27 Brazilian states for the year 2008. However, we share the limitation of most of the literature that analyzes the relationship between international trade and GHG emissions: we account for CO_2 emissions only from energy use (combustion of fossil fuels).[4]

According to the Ministry of Science, Technology and Innovation (MCTI) (2014), energy use in 2008 accounted for approximately 18% of total GHG emissions in Brazil. However, the climate impact of the energy sector is expected to increase in the coming years. As energy use increases, as indicated by Lucon *et al* (2015), in contrast to many other major emerging economies, Brazil's energy mix is becoming more carbon intensive, not less. Figure 2 shows the domestic energy supply from renewable and non-renewable sources (in thousand toe) from 2005 to 2014. Although renewable sources still account for a significant share of the energy mix (39.4% in 2009), it decreased 6.2 pp since 2008. Thus, we observe an increased reliance on fossil fuels in Brazil. Additionally, Lucon *et al* (2015) states that the investments foreseen by the federal government in the Ten-Year Energy Expansion Plan – PDE 2013, with more than 70% of R$1.3 trillion directed to fossil fuels, is likely to lock in Brazilian energy infrastructure toward a long-term carbon-intensive pathway.

[3] Other states have published official inventories that comprehend only some emission sectors, namely, Amazonas (electric power sector) and Bahia (energy sector and industrial processes). Although comprehensive, for the energy sector the inventory of Acre covers only electric power generation and emissions from automobiles.
[4] For example, Douglas and Nishoka (2012), Wiebe *et al* (2012), Davis and Caldeira (2010), and Nakano *et al* (2010) account only for CO2 emissions from fossil fuel combustion, as is the case in our study. Peters *et al* (2011) also consider CO2 emissions from cement production and gas flaring. Hertwich and Peters (2009) consider GHGs not including the sources and sinks of land use change, which is the same as the WIOD project. In addition to the absence of data on land use change with the necessary detail, the authors indicate that this source of GHGs presents difficulties in allocating emissions to economic activities.

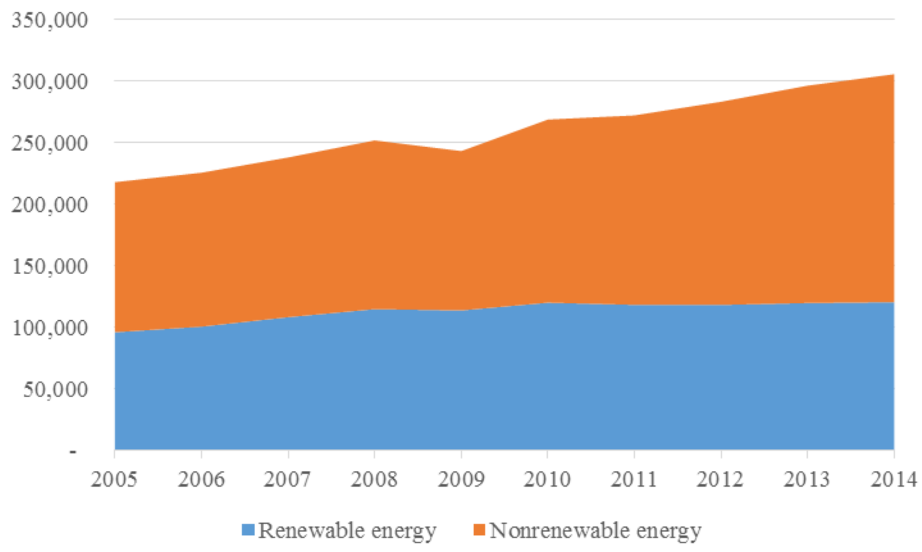

Figure 2 – Renewable and nonrenewable sources in domestic energy supply (thousand toe), 2005 to 2014

Source: EPE (2015). Prepared by the author.

Decree nº 7 390, dated December 9, 2010, which regulates PNMC, presents official projections for GHG emissions in Brazil for the year 2020. According to the projections, the GHG emissions from energy use are estimated to be 868,000 Gg in 2020 (about 140% larger than in 2008) amounting to 27% of total projected GHG emissions. Data for recent years show an even more relevant participation of emissions from energy use. In 2012, energy use accounted for approximately 37% of total GHG emissions (MCTI, 2014) given the sharp decline in emissions because of land-use change in the Amazon region since 2009. Given the growing importance of energy use in the Brazilian GHG scenario and the country's central role in global emissions, Brazil's climate impact and the relationship with economic activities are increasingly relevant.

To summarize, the objective of this paper is to trace CO_2 emissions embodied in Brazilian states' trade both within the country and internationally. The aim is to contribute to climate change policies that account for interrelationships between states in economic and environmental terms. The interrelationships between states is relevant in large and heterogeneous countries such as Brazil, where the regional distributive aspect of mitigation policies is a concern. However, the regional distributive aspects have been neglected by both national policies and subnational climate change policies, and the effectiveness of policies is hampered by deficiencies in top-down coordination.

Recognizing the interconnectedness of domestic and global value chains, we apply a country-state IO table, which explicitly displays the Brazilian states' economic interrelationships and their relations with foreign countries. To extend the model environmentally, we have compiled a novel database reflecting CO_2 emissions from energy use by state and productive industry. This database will be useful subsequently for several applications at the regional level in Brazil for the analysis of various aspects of energy use and CO_2 emissions.

In the empirical analysis, we quantify Brazilian states' trade in CO_2 emissions (i.e., the levels of CO_2 embodied in states' trade). With this, we evaluate the impact of states' interrelationships on CO_2 emissions. Reorganizing these results in terms of production-based and consumption-based emissions, we situate the Brazilian states with respect to environmental responsibilities, which has substantial implications for climate policies. Our analysis does not reveal a clear pattern for CO_2 emissions embodied in states' trade, as we find large variations across trade partners. With the goal of adding to more careful climate policies, we develop our analysis along the following lines. First, we closely examine the flows of trade in CO_2 emissions. Then, we analyze the variations in emission intensities across states. Finally, to illustrate possible climate policy tools, we verify the potential impact of enforcing a "Clean Development Mechanism" among Brazilian states.

Following this introduction, this paper is organized as follows: section 2 presents the methodology used in the empirical analysis and the newly compiled database on energy use and CO_2 emissions for Brazilian states. The results are then analyzed in section 3, and the last section presents our concluding remarks.

2. Methodology

2.1. Estimating the country-state input-output table

In order to analyze at regional level the current relationship between Brazil's CO2 emissions and domestic and global value chains, in this study we adopt the framework proposed by Dietzenbacher *et al* (2013) for combining a world input-output table (WIOT) with an inter-regional input-output table (IRIOT), thus estimating a country-state input-output table for Brazil. In this approach, we do not to take one of the datasets (say the WIOT) as a starting point and adapt the other dataset (i.e. the IRIOT) accordingly, instead we construct input coefficients for which both datasets are used.

For the empirical application, we will use the WIOT for 2008 that was constructed in the WIOD project (see Dietzenbacher *et al*, 2013b).[5] It is a full inter-country input-output table covering 40 countries and the rest of the world as a 41st "country".[6] One of the countries included is Brazil. The IRIOT for 2008 is for Brazil and covers the 27 Brazilian states (GUILHOTO *et al*, 2010). Both the WIOT and the IRIOT were aggregated to 28 compatible industries.

2.2. CO2 emissions data for Brazilian states

We account for CO_2 emissions from fossil fuels in the economic sectors.[7] Our data also includes the CO_2 emissions that are generated in thermal power plants and from the use of coke in iron and steel mills. Adopting a bottom-up approach, we obtain the levels of CO_2 emissions by industry at the state level in Brazil. For the other countries in our model, we use the CO_2 emissions data from the WIOD project.

First, we depart from the Brazilian Energy Balance (EPE, 2009) and reconcile the data from state energy balances accordingly. For the year 2008, official energy balances are available for the following states: Alagoas, Bahia, Goiás, Minas Gerais, Rio de Janeiro, São Paulo, Paraná, and Rio Grande do Sul. For Ceará and Espírito Santo, we consider participation in the national energy use and sectors' fuel structure from the energy balances of 2007 and 2010, respectively.[8]

Following Montoya *et al* (2014), we reconcile the data on fossil fuel use (in toe) from the energy balances with the industry classification of Brazil's IRIOT. Next, we estimate the corresponding CO_2 emissions by adopting the carbon emission factors and oxidation fractions

[5] The full database from the WIOD project (including a time series of WIOTs) is publicly and free of charge available at: http://www.wiod.org/database/index.htm.
[6] The countries in the WIOD's world input-output tables are: Australia, Austria, Belgium, Brazil, Bulgaria, Canada, China, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, India, Indonesia, Ireland, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Malta, Mexico, Netherlands, Poland, Portugal, Romania, Russia, Slovak Republic, Slovenia, Spain, Sweden, Taiwan, Turkey, United Kingdom, and USA (Dietzenbacher *et al*, 2013).
[7] The following fuels were considered: natural gas, steam coal, metallurgical coal, diesel oil, fuel oil, gasoline, LPG, kerosene, gas coke, coal coke, other oil by-products, and coal tar.
[8] The sources for state energy balances are: Alagoas (2012), Bahia (2009), Ceará (2008), Espírito Santo (2013), Goiás (2009), Minas Gerais (2011), Paraná (2011), Rio de Janeiro (2013), Rio Grande do Sul (2010), and São Paulo (2009).

from the Brazilian Inventory of Anthropogenic Emissions and Removals of Greenhouse Gases (MCTI, 2010).

From this approach, approximately 75% of Brazil's CO_2 emissions from energy use in 2008 were attributed to the 10 aforementioned states that publish official energy balances. The differences from the national total by sector are allocated to the other states according to their respective gross output.

In our application, we disregard the CO_2 emissions from households' direct use of fossil fuels (approximately 9% of the national emissions). Instead, we focus on the emissions generated by the various economic industries in their productive activities.

2.3. Trade in CO2 emissions (TiCE)

To investigate the interregional (and international) spillover of CO_2 emissions, we apply an adaptation of the concept of trade in value added (TiVA) (MENG *et al*, 2013) for our country-state IO system. The adaptation approximates the methodology of Peters (2008) based on multi-regional IO analysis.

From the basic Leontief model, the total output of an economy can be expressed as the sum of intermediate consumption and final consumption (MILLER; BLAIR, 2009)

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{y} \tag{1}$$

$$(\mathbf{I} - \mathbf{A})^{-\mathbf{1}} = \mathbf{B} \tag{2}$$

$$\mathbf{x} = \mathbf{B}\mathbf{y} \tag{3}$$

where $\mathbf{x}$ is the $n \times 1$ total output vector (n is the number of industries in the system), $\mathbf{A}$ is the $n \times n$ direct input coefficients matrix, $\mathbf{y}$ is the $n \times 1$ final demand vector, and $\mathbf{B}$ is the Leontief inverse matrix.

Considering $\mathbf{C}$ as the $n \times n$ diagonal matrix of CO_2 emissions coefficients, we can describe the CO_2 emissions related IO model as:

$$\mathbf{q} = \mathbf{C}\mathbf{x} \tag{4}$$

from (3):

$$\mathbf{q} = \mathbf{C}\mathbf{B}\mathbf{y} \tag{5}$$

$$\mathbf{CB} = \mathbf{K} \tag{6}$$

$$\mathbf{q} = \mathbf{Ky} \tag{7}$$

where $\mathbf{q}$ is the $n \times 1$ CO_2 emissions vector, and $\mathbf{K}$ is the CO_2 emissions-related Leontief inverse.

In our empirical analysis, we apply a state-country IO model. Therefore, the matrix $\mathbf{K}$ above can be decomposed as follows, considering r regions (states or countries):

$$\begin{bmatrix} \mathbf{K}^{11} & \dots & \mathbf{K}^{1r} \\ \vdots & \ddots & \vdots \\ \mathbf{K}^{r1} & \dots & \mathbf{K}^{rr} \end{bmatrix} = \begin{bmatrix} \mathbf{K}^{11} & \dots & \mathbf{0} \\ \vdots & \ddots & \vdots \\ \mathbf{0} & \dots & \mathbf{K}^{rr} \end{bmatrix} + \begin{bmatrix} \mathbf{0} & \dots & \mathbf{K}^{1r} \\ \vdots & \ddots & \vdots \\ \mathbf{K}^{r1} & \dots & \mathbf{0} \end{bmatrix} \tag{8}$$

In equation (4.8), the elements of the first term of the sum can be considered intra-regional effects, representing impacts on the CO_2 emissions of sectors of a region from exogenous changes in the final demand of the same region. On the other hand, the elements of the second term of the sum can be regarded as spillover effects, representing impacts on the CO_2 emissions of sectors of a region from exogenous changes in the final demand of the other region.

In our application, we are interested in estimating the contribution of the final demand in each region to the total CO_2 emissions of each region. We construct the $\mathbf{Y}$ $(r.n) \times r$ final demand matrix by the horizontal concatenation of final demand vectors of each region in our model. Therefore, the dimensions of the above matrices and vectors become: a) $\mathbf{X}$, $\mathbf{Y}$, and $\mathbf{VQ}$, size $[(r.n) \times r]$; b) $\mathbf{A}$, $\mathbf{B}$, and $\mathbf{K}$, size $(r.n) \times (r.n)$. We rewrite equation (4.7) considering r regions in the model

$$\mathbf{Q} = \mathbf{KY} \tag{9}$$

and quantify the emissions under a consumption-based accounting principle (see Pei *et al*, 2015; Peters *et al*, 2011; Davis and Caldeira, 2010). Figure 3 illustrates the framework for trade in CO_2 emissions (TiCE) as represented in matrix $\mathbf{Q}$:

			Final demand			Production-based emissions
			Region 1	...	Region r	
CO_2 from region - industries	Region 1	Industry 1	q_1^{11}	...	q_1^{1r}	$\sum_j q_1^{1j}$
		...	...	...	...	...
		Industry n	q_n^{11}	...	q_n^{1r}	$\sum_j q_n^{1j}$
	...	...	...	...	...	...
	Region r	Industry 1	q_1^{r1}	...	q_1^{rr}	$\sum_j q_1^{rj}$
		...	...	...	...	...
		Industry n	q_n^{r1}	...	q_n^{rr}	$\sum_j q_n^{rj}$
Consumption-based emissions			$\sum_s \sum_i q_s^{i1}$	...	$\sum_s \sum_i q_s^{ir}$	World emissions

Figure 3 – Framework for trade in CO_2 emissions (matrix Q)

Note: Cell values represent the CO_2 generated in the region-industry in the row because of the final demand of the region in the column.

Here, q_s^{ij} is the CO_2 emissions generated directly and indirectly in industry *s* of region *i* in response to the final demand of region *j*. For a given region, the sum of CO_2 emissions that its final demand causes across all industries and regions constitutes its consumption-based emissions given in the bottom row of Figure 4.3. On the other hand, for a given industry, the sum of the CO_2 emissions it generates, regardless of the consumer region, equals its production-based emissions given in the last column in Figure 4.3. The summation of consumption-based emissions across all consumer regions and the summation of production-based emissions across all producer region-industries equals world emissions.

In this framework, we define:

a) Emissions in region *E* due to its domestic final demand: $\sum_s q_s^{EE} = \sum_k \mathbf{K}^{Ek}\mathbf{y}^{kE}$ (10)

b) Exports of CO_2 of region *E*: $\sum_s \sum_{j \neq E} q_s^{Ej} = \sum_k \sum_{j \neq E} \mathbf{K}^{Ek}\mathbf{y}^{kj}$ (11)

c) Imports of CO_2 of region *E*: $\sum_s \sum_{i \neq E} q_s^{iE} = \sum_k \sum_{i \neq E} \mathbf{K}^{ik}\mathbf{y}^{kE}$ (12)

d) Production-based emissions of region *E* (sum of (10) and (11)):

$$\sum_s \sum_j q_s^{Ej} = \sum_k \sum_j \mathbf{K}^{Ek}\mathbf{y}^{kj} \quad (13)$$

e) Consumption-based emissions of region *E* (sum of (10) and (12)):

$$\sum_s \sum_i q_s^{iE} = \sum_k \sum_i \mathbf{K}^{ik}\mathbf{y}^{kE} \quad (14)$$

3. Main results

Our results concern CO_2 emissions solely from energy use in the year 2008. We divide our results into six subsections. First, we present the aggregated results for TiCE for the Brazilian states and countries in our model, assessing the participation of traded components in global emissions. Then, these results are reorganized as production-based and consumption-based emissions, proceeding to the net emission transfers of each region. We further analyze the TiCE results for Brazilian states with respect to trade partners. In the following subsection, we analyze the intensity of both production-based and consumption-based CO_2 emissions, as well as the relationship of consumption-based emissions with final demand expenditures. The last subsection presents the results for an exercise that considers the replication of the best sectoral energy use technologies for all Brazilian states.

3.1. Traded components of global CO2 emissions

Table 1 summarizes the results for TiCE. The first column is obtained by properly applying equation (10). Taking *j* in equation (11) as Brazilian states, we obtain the second column; taking *j* as foreign countries, we obtain the fourth column. Accordingly, we obtain the third and fifth columns considering *i* in equation (12) as Brazilian states and foreign countries, respectively.[9]

Table 1 shows that, as expected for a country as heterogeneous as Brazil, the values of traded components of CO_2 emissions vary greatly among the states.[10] The states in the Southeast region (Espírito Santo, Minas Gerais, Rio de Janeiro, and São Paulo) present the greatest sums of domestically consumed, interregionally and internationally traded CO_2 emissions. São Paulo's shares were the largest, except for exports of CO_2 emissions to foreign countries for which Minas Gerais led.

[9] We distinguish between inflows/outflows for trade between domestic states and imports/exports for trade between states and foreign countries or between foreign countries.

[10] In this section, we aggregate some of the countries in our model as "Other EU27" (Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, Greece, Hungary, Ireland, Lithuania, Luxembourg, Latvia, Malta, the Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, and Sweden) and as "Other countries + RoW" (Australia, Indonesia, Turkey, and ROW) for presentation purposes. We aggregate only the final results; all the calculations use the full model composed of 67 distinct regions (27 Brazilian states + 39 countries + RoW).

Considering the TiCE results in Brazil compared to those of other countries globally, the figures are small. Concerning the relationship of Brazilian states and foreign countries, as shown in the second and third columns of Table 1, the largest amounts of exports to and imports from Brazilian states correspond to countries that are not treated individually in our model (i.e., the "rest of the world" region). However, it is notable that China's exports of CO_2 to Brazilian states represent almost 30% of this component.

Table 1 – Allocation of global CO_2 emissions separated into domestic, interregionally and internationally traded components (in thousand tons)

	Domestic	Exports (outflows) to Brazilian regions	Imports (inflows) from Brazilian regions	Exports to foreign countries	Imports from foreign countries
Acre	236	135	384	31	160
Amapá	240	72	430	123	226
Amazonas	1,956	4,238	1,800	864	3,580
Pará	2,430	1,956	4,194	5,325	2,111
Rondônia	744	713	1,145	224	611
Roraima	146	83	212	16	95
Tocantins	542	479	769	142	419
Alagoas	773	576	1,114	219	521
Bahia	8,488	6,296	7,050	4,946	5,493
Ceará	2,527	1,069	3,330	317	2,093
Maranhão	1,902	2,613	2,027	2,030	1,819
Paraíba	1,255	820	1,884	137	1,074
Pernambuco	4,372	3,274	3,794	857	2,827
Piauí	908	383	1,410	105	656
Sergipe	968	1,344	1,034	308	579
Rio Grande do Norte	1,070	873	1,726	278	777
Distrito Federal	3,842	1,402	5,012	205	2,669
Goiás	4,369	2,879	3,778	1,444	2,786
Mato Grosso	1,900	3,337	2,005	2,197	1,043
Mato Grosso do Sul	1,651	1,886	1,550	852	1,302
Espírito Santo	1,920	7,826	2,796	9,241	2,134
Minas Gerais	16,478	14,585	11,500	14,110	9,301
Rio de Janeiro	18,909	12,718	16,075	7,590	10,833
São Paulo	34,522	26,581	24,635	13,209	33,255
Paraná	7,867	8,986	6,463	3,586	7,308
Santa Catarina	6,023	7,265	4,995	2,957	5,116
Rio Grande do Sul	7,722	6,212	7,490	3,567	7,194
Brazil	133,759	118,602	118,602	74,880	105,982
China	3,423,810	29,829	6,502	2,037,241	438,670
India	1,021,366	3,279	778	240,880	186,831
Russia	859,049	5,378	1,274	468,338	137,248
USA	3,873,706	9,141	13,725	474,513	1,183,184
Mexico	262,729	630	1,798	60,796	118,411
Canada	243,070	2,861	1,542	150,580	186,898
Germany	383,696	3,737	4,448	242,989	422,677
Spain	167,355	726	1,569	66,901	171,705
France	167,220	809	2,249	78,092	262,037
Great Britain	307,722	1,184	1,862	121,335	270,579
Italy	248,004	1,206	2,143	100,944	225,623
Other EU27	840,613	4,528	6,601	410,874	638,175
Japan	751,063	2,243	2,834	207,223	419,360
Korea	294,521	2,116	1,353	186,160	169,024
Taiwan	127,234	1,757	601	138,882	65,032
Other countries + RoW	3,895,511	36,558	25,600	1,490,581	1,580,873
Foreign countries	16,866,669	105,982	74,880	6,476,329	6,476,329

From the TiCE results we quantify the importance of international trade with respect to global CO_2 emissions, shown in Chart 2. In 2008, 29% of global CO_2 emissions, or 6.9 Gt CO_2, were attributed to international trade. This approximates the findings of other authors (Peters *et al* (2011): 26% in 2008; Davis and Caldeira (2010): 23% in 2004). China's exports of CO_2

emissions alone represented 31% of the internationally traded emissions, or 9% of global emissions.

Emissions from the production of interstate traded goods and services in Brazil amounted to 36% of the country's territorial (or production-based) CO_2 emissions. International trade was less relevant for Brazilian emissions than the world average as 23% of Brazil's territorial CO_2 emissions were embodied in its exports to foreign countries.

Interstate and international trade are more relevant to the generation of global and Brazil's CO_2 emissions than for value added, which is emphasized by the comparison with the figures for trade in value added (TiVA) in Chart 2. In 2008, 21% of global value added was attributed to international trade (versus 29% for CO_2 emissions). In Brazil, interstate trade accounted for to 27% of the country's value added (versus 36% for CO_2 emissions). The greater relevance of interregional trade for generating CO_2 emissions (in comparison with value-added) also holds for every state in Brazil.

Chart 2 – Participation of interstate and internationally traded components

Participation of traded components in CO_2 emissions	
Global CO_2 emissions:	23,776,219 kt
Emissions in international trade:	6,919,108 kt → 29% of global emissions
Brazil's production-based CO_2 emissions:	327,240 kt
Emissions in international trade:	74,880 kt → 23% of Brazil's emissions
Emissions in interstate trade:	118,602 kt → 36% of Brazil's emissions
Participation of traded components in value added	
Global value added:	59,869,267 million US$
Value added in international trade:	12,667,732 million US$ → 21% of global VA
Brazil's value added:	1,546,495 million US$
Value added in international trade:	195,610 million US$ → 13% of Brazil's VA
Value added in interstate trade:	420,706 million US$ → 27% of Brazil's VA

3.2. Production-based and consumption-based CO2 emissions

To quantify the emission transfers by means of interregional and international trade, we rearrange the results of TiCE presented in Table 1. To compute the production-based emissions, we sum the components "domestic," "exports (outflows) to Brazilian regions," and "exports to foreign countries," as in equation (13). For consumption-based emissions, we sum "domestic," "imports (inflows) from Brazilian regions," and "imports from foreign countries," as in equation (14). The difference between production-based and consumption-based emissions is defined as "net emission transfer" via trade (PETERS *et al*, 2011). Here, we are considering the transfers via international and interregional trade inside Brazil. Thus, the net emission transfer corresponds to CO_2 emissions in each region (state or country) from goods and services production that are ultimately consumed in a different region minus the emissions in other regions to produce goods and services that are ultimately consumed in the first region. Following the sign convention for an economic balance of trade, net exports are positive and net imports are negative.

For the Brazilian states, where emission transfers also happen via interregional trade, of 27 states, seven were sources of net emission transfers to other states or foreign countries. Espírito Santo and Minas Gerais were outstanding net exporters of CO_2 emissions. São Paulo, the greatest emitter in the country of both production and consumption-based emissions, was also the recipient of the largest net emission transfer. These results are analyzed with further detail in the next section.

Considering Brazil as a whole, the country's consumption-based emissions surpassed its production-based emissions giving the country a net emission transfer via international trade. This is different for the other BRIC countries, which presented positive net emission transfers via international trade, particularly China, with net export emissions amounting to 1.6 Gt CO_2. Concerning the countries included in Annex B of the Kyoto Protocol and that are treated individually in our model, each of them (with the exception of Bulgaria, Denmark, Estonia, Poland, and Russia) received net emission transfers via international trade. This finding adds to the literature concerning the inadequacy of the territorial principle for mitigation targets under a fragmented, two-tier mitigation strategy as in the Kyoto Protocol (PETERS *et al*, 2011).

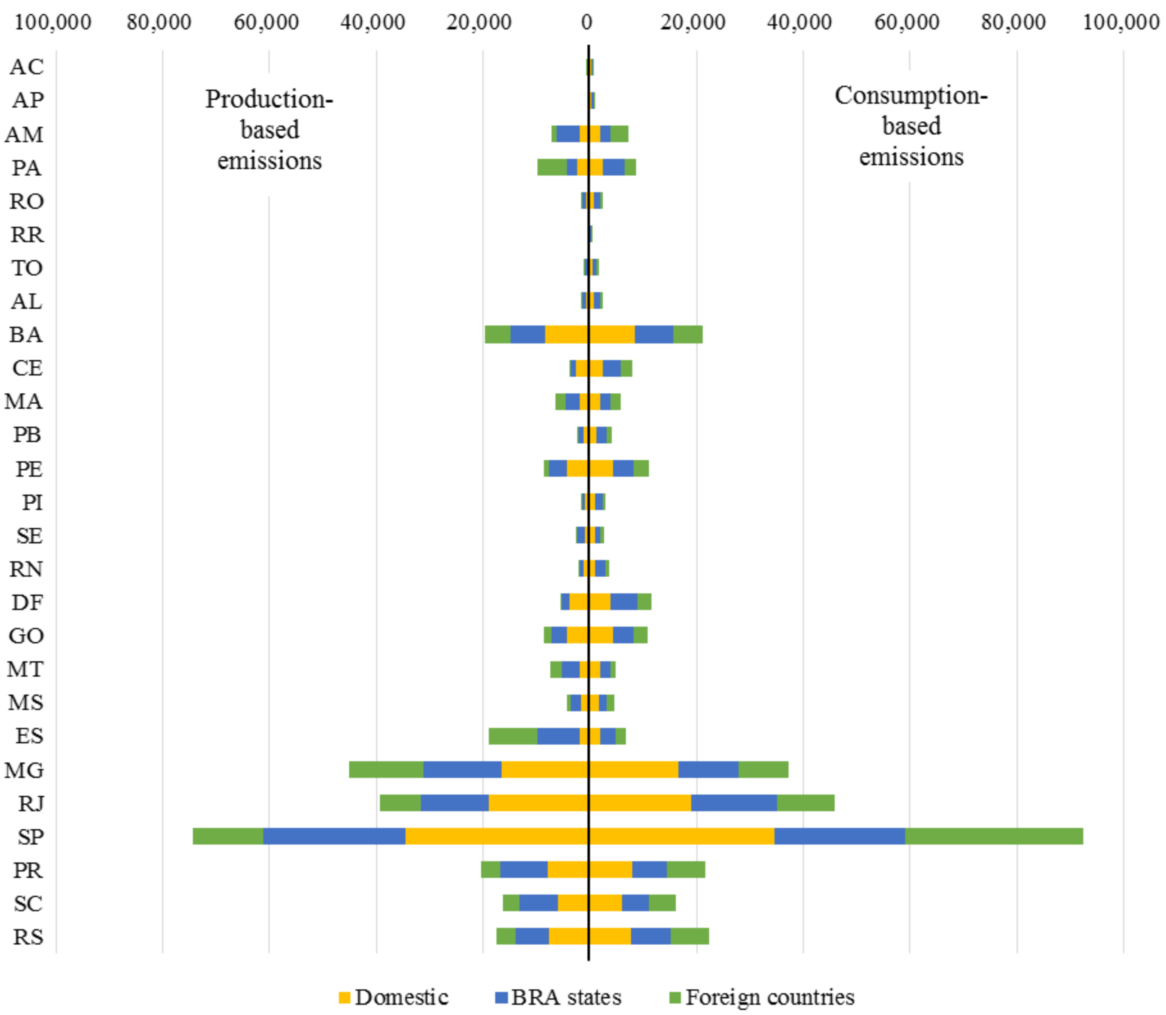

Figure 4 – Production-based and consumption-based CO_2 emissions (in thousand tons), Brazilian states

Figure 5 breaks down these results by groups of trade partners (domestic components, Brazilian states, and foreign countries). The figure shows great variation in the significance of both interregional and international traded components among both Brazilian states and foreign countries.

A total of 36% of the Brazilian production-based CO_2 emissions were attributed to interstate trade. Across the states, this ranges from 17% in Amapá to 60% in Amazonas. The internationally traded component of CO_2 emissions also has great variance among the states corresponding to shares of production-based CO_2 emissions that range from 4% in Distrito Federal to 55% in Pará. The importance of the internationally traded component of CO_2 emissions in Espírito Santo is also outstanding (49% of production-based CO_2 emissions in this state), and only 10% of this state's CO_2 emissions were because of the state's own final demand.

Among the foreign countries, Taiwan is where international trade presented the most important role in production-based CO_2 emissions (52%). Although China was the largest exporter of CO_2 emissions in the world, the internationally traded component was (slightly) less important than in, for example, Germany and Korea given the extent of the Chinese domestic final demand. This observation also applies to the internationally traded component of CO_2 emissions in the USA from the consumption perspective. Although the USA is by far the greatest importer of CO_2 emissions, the internationally traded component is more relevant for the EU countries, for example.

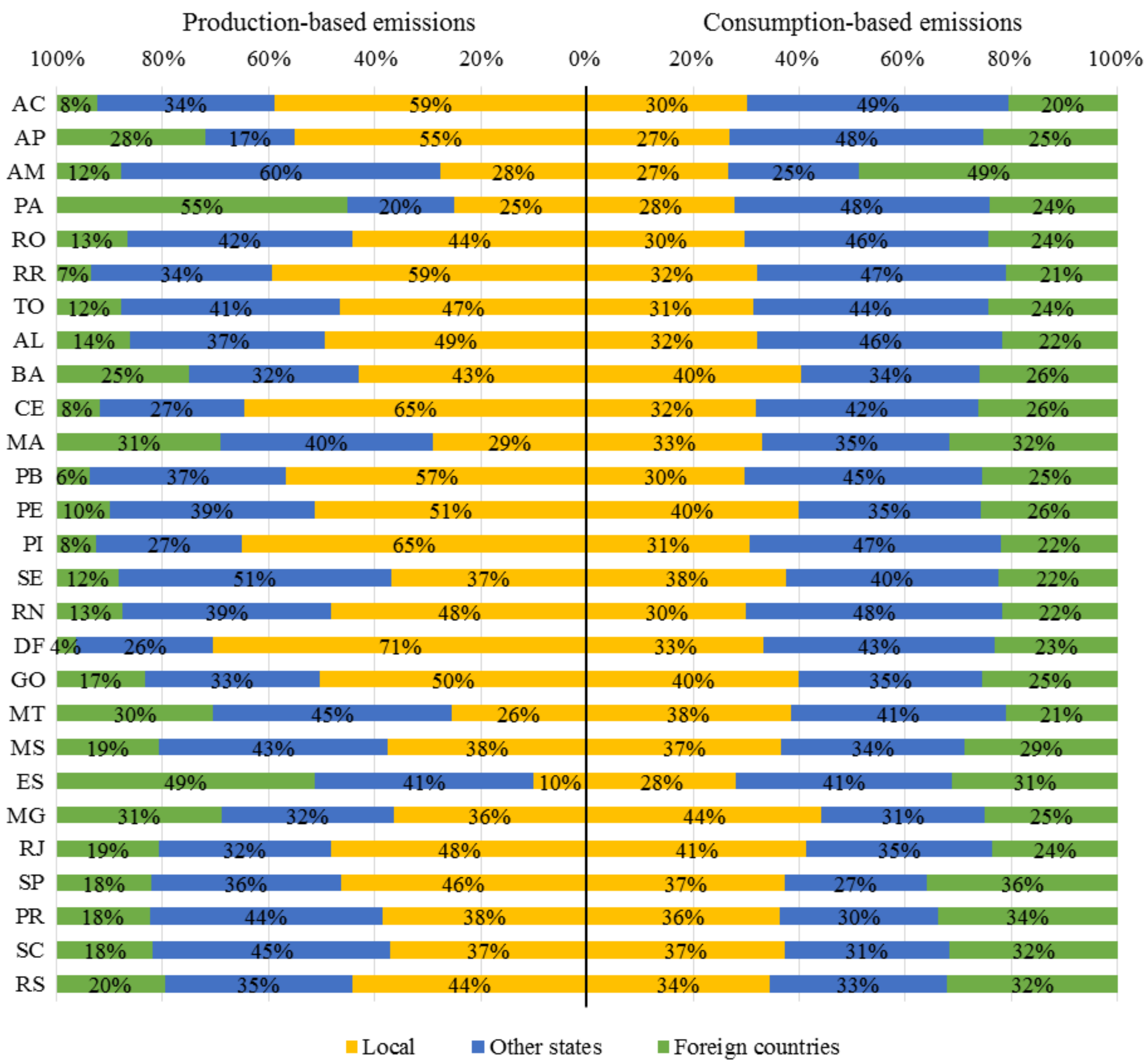

Figure 5 – Participation of domestic, Brazilian states, and foreign countries' components in production-based and consumption-based CO_2 emissions (%), Brazilian states

3.3. Brazilian states' inter-regional and international trade in CO2 emissions

In this sub-section, we analyze with further detail the results for Brazilian states' TiCE, since it is relevant for policy purposes to identify and quantify the most important CO2 emissions flows, between each pair of trade partners.

Table A1, in the Annex, summarizes the inter-regional flows in CO2 emissions, with aggregation across the 28 industries of our model. An important share of Brazil's inter-regional TiCE (23%) took place among the states in the Southeast region. São Paulo is dominant in the inter-regional trade in CO2 emissions, responding for 22% of outflows and 21% of inflows of emissions in Brazil. For all the states, São Paulo is the most important source of inter-regional TiCE and, except for Roraima, Alagoas, and Distrito Federal, it is also the most important destination. São Paulo's most important trade partners (in CO2 emission terms) are the other states in the Southeast region, for which São Paulo sources 37% of its outflows and from which it acquires 44% of its inflows. The key emission flows from São Paulo to Rio de Janeiro and from Minas Gerais to São Paulo alone amounted respectively in 5% and 4% of Brazil's inter-regional TiCE. However, it is noteworthy that comparing this with the results from the TiVA analysis (DIETZENBACHER *et al*, 2013) reveals that São Paulo's dominance is less intense in terms of emissions – the state responded for the larger share of 37% of outflows in value added terms. This is because São Paulo presents a low consumption-based CO2 emissions intensity, will be seen in the next section. Despite such low intensity, São Paulo's inter-regional trade flows (in value added terms) are so large that the state also takes the lead in TiCE.

On the other hand, Espírito Santo and Minas Gerais are more relevant as sources for inter-regional TiCE (than for TiVA). This is largely due to the large amounts of CO2 emission that are generated in their "Mining and Quarrying" and "Basic Metals and Fabricated Metal" sectors in response to the final demands of other states. For both states, Rio de Janeiro and São Paulo were the most important destinations of their outflows, concentrating more than 46% of them.

In fact, the highest intensity of CO2 corresponds to the flows from Espírito Santo: on average, for each US$ one million of value added due other states' final demand, 0.78 thousand ton of CO2 emissions was produced there (in the whole inter-regional system, the average was 0.28 thousand ton of CO2 emissions / US$ one million of value added). Bahia's outflows presented the second highest CO2 intensity, 0.49 thousand ton of CO2 emissions / US$ one million of value added, quite below Espírito Santo's.

From the data in Table A1, we can compute the net emission transfers between the states. Due to space limitation, here we only describe some of the main results. Espírito Santo was a source of net emission transfers to every other state in Brazil. Its largest surplus was with São Paulo (1.9 thousand ton of CO2). Surpluses of TiCE were also verified for Amazonas with all trade partners in Brazil (except Espírito Santo). The latter result is mainly due to the Free Trade Zone of Manaus, which comprehends an industrial hub directed to the demand of the rest of the country. In the case of São Paulo, differently for what was observed considering TiVA (DIETZENBACHER *et al*, 2013), when the state presented surpluses with all other states (except Amazonas), here the sum of its deficits (especially with Espírito Santo and Minas Gerais) greatly compensates its surpluses in inter-regional trade in CO2 emissions. This results in its positive net emissions transfer to other states amounting in only 3% of its consumption-based CO2 emissions. On the other hand, the state that received the largest net emission transfer via inter-regional trade was Distrito Federal, what is comprehensible given its limited productive structure and its high final demand expenditures. In 2008, it received 3,610 thousand tons of CO2 from other states, in net terms (corresponding to 66% of its production-based CO2 emissions).

The states' exports and imports in CO2 emissions are respectively detailed by trade partner in Tables A2 and A3[11], in the Annex. According to Table A2, the main exporter of CO2 emissions was Minas Gerais (almost 19% of the national exports), which surpassed São Paulo (about 17% of national exports). Corresponding to approximately 12.5%, Espírito Santo also stands out. Concerning the exports by trade partners, the largest share (34%) corresponded to the group of countries "Other + ROW", being followed by EU 27 (25.2%), USA (18.4%) and China (8.7%). However, this ranking of trade partners does not hold for every state. For Pará and Espírito Santo, the USA are more important destination of exports of CO2 than EU27.

It is interesting that, on average, Brazil's exports are more intense in CO2 emissions than its inter-regional flows (0.38 thousand ton of CO2 emissions / US$ one million of exported value added versus 0.28 in inter-regional trade). As observed for total production-based CO2

[11] In the next Tables, for better presentation, the countries in our model are classified as follows: CHN: China; IND: India, RUS: Russia; USA: United States; MEX: Mexico; CAN: Canada; DEU: Germany; ESP: Spain; FRA: France; GBR: United Kingdom; ITA: Italy; Other EU27: Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, Greece, Hungary, Ireland, Lithuania, Luxembourg, Latvia, Malta, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, and Sweden; JPN: Japan; KOR: Korea; TWN: Taiwan; ther + ROW: Australia, Indonesia, Turkey, and ROW.

emissions and inter-regional outflows, the intensity of Espírito Santo's exports of CO2 emissions was the highest in Brazil (1.08 thousand ton of CO2 emissions / US$ one million of exported value added, on average). We observe that the average CO2 intensity varies with the trade partner. So, in Brazil as whole, USA's final demand generates a higher CO2 / value added ratio than China's or EU27's (0.44 thousand ton of CO2 emissions / US$ one million of exported value added versus 0.37).

São Paulo was largely dominant in the imports in CO2 emissions (31% of national imports). In fact, the emission transfer of foreign countries to São Paulo greatly surpassed those via inter-regional trade, i.e. the final demand of São Paulo had a greater impact in CO2 emissions of foreign countries than in other states of Brazil. Thus the main sources of emission transfer to São Paulo were the group "Other + ROW", China, EU27, and the USA, before even the states in Brazilian southeast region. The group "Other + ROW" and China produced the largest amounts of CO2 emissions in foreign countries due to Brazilian states' final demand (34% and 28%, respectively), being followed by EU27 (12%) and the USA (9%).

Concerning the CO2 intensities of Brazilian states' imports of CO2 emissions, it is noticeable that BRICs exports to Brazil presented quite high CO2 / value added ratio. In the case of China, for example, each US$ one million of exported value added to Brazilian states embodied 1.46 thousand ton of CO2 emissions. This reflects the high intensity of the production-based CO2 emissions in these countries, as presented in the next section.

Combining the data in Tables A2 and A3, we obtain the net emission transfers relating Brazilian states and foreign countries. São Paulo received a large net emission transfer from foreign countries in 2008 (20,046 thousand tons). In fact, from the countries depicted in Tables A2 and A3, São Paulo presented net imports with all of the (except Mexico, Spain, and France). On the other hand, Espírito Santo, Minas Gerais, and Pará were important net exporters of CO2 emissions to foreign countries. Especially Espírito Santo, which was a source of net emission transfers amounting in 7,107 thousand tons CO2. Considering the foreign trade partners, the BRICs and the group "Other + ROW" were sources of net emission transfers to almost every state in Brazil. China outstands, presenting a total net emission transfer of 23,327 thousand tons to Brazilian states. On the other hand, the countries from UE27 and the USA were net importers of CO2 emissions in Brazil as a whole.

3.5. Intensity of CO2 emissions

For policy purposes, it is relevant to assess the intensity of emissions in addition to the magnitude of production and consumption-based CO_2 emissions flows. Table 2 presents the results for production-based and consumption-based intensities.

For production-based emissions, intensity can be evaluated by the ratio between the total emissions and the total value added in a region. The Brazilian economy was less intensive in production-based CO_2 emissions than the world average (0.21 thousand tons of CO_2/US$ 1 million of value added in 2008; world average: 0.40) and all the developing countries depicted in Table 4.2. The other three BRICs, notably China, presented production-based CO_2 intensities much larger than the world average in 2008.

For the Brazilian states, it is relevant that São Paulo, the main state in economic terms, presented an intensity of production-based CO_2 emissions that was smaller than the national average (0.15 thousand tons of CO_2/US$ 1 million of value added). This reflects the low average energy intensity of São Paulo's industries and the advantage in clean energy production indicated by Abramovay (2010) from the state's hydroelectric plants and the importance of ethanol.[12] The three highest carbon intensities were exhibited by Espírito Santo, Minas Gerais, and Bahia, in that order. In Espírito Santo, the intensity was 0.56 thousand tons of CO_2/US$ 1 million of value added, thus, above the world average. For these states, a substantial share of their manufacturing production is conducted by polluting industries (e.g., "coke, refined petroleum and nuclear fuel," and "basic metals and fabricated metal"), but they also present above national average technical coefficients for CO_2 emissions.

We assess consumption-based CO_2 emissions in per capita terms. The results are presented in Table 2. Among the 40 countries in our model, per capita consumption-based CO_2 emissions vary from 1.03 tons per person per year (py) for India to 16.54 tons/py for the USA. Brazil's emissions (1.89 ton/py) exceeded India's but were below China's (2.88 tons/py) and the world

[12] In 2008, the energy intensity of São Paulo corresponded to 0.10 toe (of final energy use, excluding the residential sector)/US$ 1 thousand of value added while, in the rest of Brazil, energy intensity was 0.13 toe/US$ 1 thousand. According to the official energy balances, hydroelectricity and biomass were sources of approximately 50% of final energy use in São Paulo and 40% in the remainder of Brazil.

average (3.42 tons/py). Among Brazilian states, the lowest intensity corresponded to Alagoas (0.77 ton/py) while Distrito Federal was at the other extreme (4.51 tons/py, above the world average).

Table 2 – Intensity of production-based CO_2 emissions in relation to value added (thousand tons/US$ 1 million) and per capita consumption-based CO_2 emissions (ton per person per year)

	Production-based emissions (kt) / Value added (US$ millions)	Per capita consumption-based CO_2 emissions (ton / py)
Acre	0.12	1.15
Amapá	0.12	1.46
Amazonas	0.27	2.20
Pará	0.32	1.19
Rondônia	0.19	1.67
Roraima	0.10	1.10
Tocantins	0.17	1.35
Alagoas	0.16	0.77
Bahia	0.32	1.45
Ceará	0.13	0.94
Maranhão	0.31	0.91
Paraíba	0.17	1.13
Pernambuco	0.24	1.26
Piauí	0.17	0.95
Sergipe	0.26	1.29
Rio Grande do Norte	0.17	1.15
Distrito Federal	0.09	4.51
Goiás	0.23	1.87
Mato Grosso	0.27	1.67
Mato Grosso do Sul	0.25	1.93
Espírito Santo	0.56	1.98
Minas Gerais	0.32	1.88
Rio de Janeiro	0.22	2.89
São Paulo	0.15	2.25
Paraná	0.22	2.04
Santa Catarina	0.26	2.67
Rio Grande do Sul	0.17	2.06
Brazil	0.21	1.89
China	1.19	2.88
India	0.98	1.03
Russia	0.88	6.94
USA	0.30	16.54
Mexico	0.30	3.33
Canada	0.27	12.93
Germany	0.18	9.72
Spain	0.15	7.53
France	0.09	6.90
Great Britain	0.17	9.46
Italy	0.16	7.95
Other EU27	0.25	7.99
Japan	0.20	9.22
Korea	0.53	9.71
Taiwan	0.68	8.37
Other countries + RoW	0.53	1.87
Global average	0.40	3.42

Hertwich and Peters (2009) observed that per capita consumption-based CO_2 emissions are strongly correlated with per capita final demand expenditures. To examine this point, we used a regression of log-transformed data to derive cross-country elasticity. For the countries in our model, CO_2 emissions increase with final demand expenditures, as shown in Figure 6, with an elasticity $\varepsilon = 0.63$ (standard error 0.04 and $R^2 = 0.84$).[13] Therefore, as a country becomes wealthier, its consumption-based CO_2 emissions increase by 63% for each doubling of per capita final demand expenditure. Because the elasticity is less than one, the intensity of per capita consumption-based CO_2 emissions decreases with final demand expenditures.

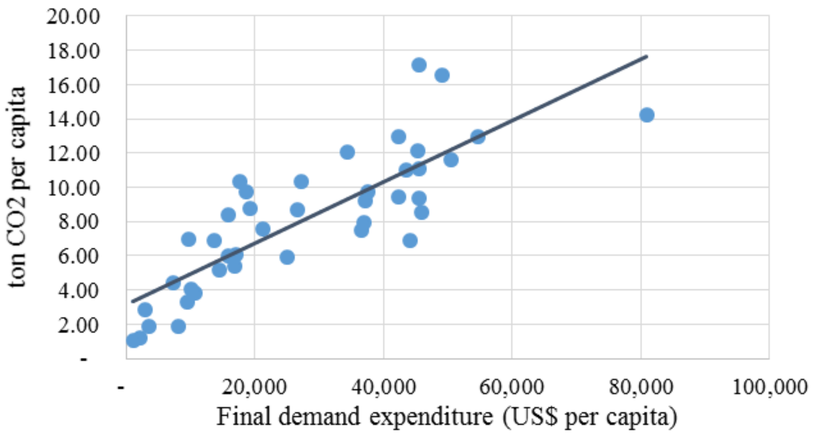

Figure 6 – Consumption-based CO_2 emissions (ton per capita) as a function of final demand expenditures (US$ per capita), countries

Applying this exercise to Brazilian states (Figure 7), we obtain an unexpected unitary cross-state elasticity $\varepsilon = 1.0038$ (standard error 0.09 and $R^2 = 0.84$). [14] The elasticity is larger than it is when we consider the countries, and the increase in consumption-based CO_2 emissions is stronger as states become wealthier. Thus, the carbon intensity of consumption in per capita terms is constant with rising expenditures across Brazilian states.

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[13] Hertwich and Peters (2009) observed a stronger increase of consumption-based CO2 emissions with expenditures across countries ($\varepsilon = 0.81$, $R^2 = 0.88$). We find it difficult to compare our results because they are sensitive to the countries included in the regression. Hertwich and Peters' database discriminates poor countries in Africa, Southeast Asia, and Latin America.

[14] In this regression, we omit Distrito Federal (per capita consumption-based CO2 emissions: 4.51 ton / py; per capita final demand expenditure: US$30,341). If this state is included, we observe cross-state elasticity $\varepsilon = 0.87$ (standard error 0.07 and $R^2 = 0.86$).

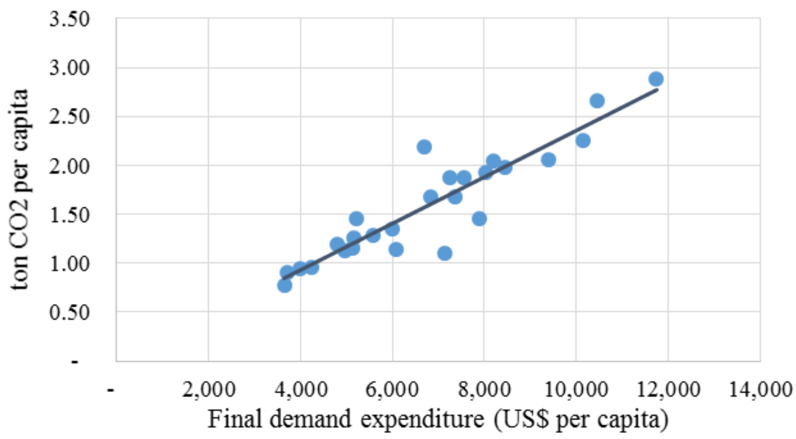

Figure 7 – Consumption-based CO_2 emissions (ton per capita) as a function of final demand expenditures (US$ per capita), Brazilian states

This result can be interpreted according to the hypothesis of the environmental Kuznets curve – an inverted U-shaped relationship between a country's income and its level of pollution (e.g., the pioneering work by Grossman and Krueger (1993)). Under this hypothesis, if the Brazilian states are at a relatively low level of development, we expect to verify a non-decreasing pollution intensity across the states, as is the case in the prior analysis (we found a unitary cross-state elasticity). Here, we only intend to note this possibility because testing the hypothesis is beyond the scope of this work.

Policy-wise, our findings cannot support the claim that the combination of better technologies and structural change concerning consumption will lead to lower carbon intensities as Brazilian states become wealthier, as verified across countries (HERTWICH; PETERS, 2009). This is an indication of the urgency for proactive climate policies, such as that analyzed in the following subsection.

3.6. Assessing the potential environmental benefit of technology transfers

The Clean Development Mechanism (CDM) is a cooperative tool established under the Kyoto Protocol that allows industrialized countries with mitigation targets to develop or finance projects that reduce GHG emissions in non-Annex I countries in exchange for emission reduction credits. Thus, CDM intends to help Annex I countries achieve their target at a lower cost while contributing to the sustainable development of host countries. According to Dechezleprêtre *et al* (2008), the CDM is considered a key way to boost the North-South transfers of climate-friendly technologies.

Peters (2008) indicated that the CDM concept is a natural part of consumption-based accounting of emissions because it identifies which industries' and countries' final demand contribute most to emissions. Therefore, consumption-based indicators, which we have analyzed, can be used to identify priority CDM mitigation activities in areas that are sources of exports/outflows of CO_2 emissions.

The differences in production-based intensities across states highlight technology transfers as possible mitigation strategies. To verify the potential environmental benefit from a mechanism of this type inside Brazil, we assess the extent to which Brazil's CO_2 emissions could be reduced via technology transfer if each sector in every state adopted the best available technology in the country in emission terms. We assume that a Brazilian state can adopt the productive technology from another state more readily or less costly than a technology from a foreign country. With this in mind, we restrain the set of technologies that are available to transfers to those existing in the country in 2008 as described by the IO relations in our model.

In our simple exercise, we have not made a distinction between host parties and "parties in Annex I" as in the global CDM, and every state can be both a host and source of technology transfers (e.g., São Paulo is a source for the transfer of climate-friendly technology to Rio de Janeiro in the "transports" industry because of this industry's particular technology, but São Paulo is a host to technology transfer from Rio de Janeiro for the "mining and quarrying" industry).

Thus, we attribute CO_2 coefficients that represent the cleanest technology available for the productive industries in Brazil, as in 2008. Our results can be interpreted as potential reduction of CO_2 emissions because of energy use in the productive sectors given the technologies available within the country in 2008.[15]

In Brazil, with the transfer of the cleanest sectoral technologies, production-based CO_2 emissions would decline by 152,819 thousand tons. That is, under a technology transfer

[15] The simulation relies on perfect transfers of technology between states including the energy intensities in the productive activities but also the composition of the energy matrices (i.e., participation of renewable sources and fossil fuels in energy supply).

mechanism, production-based emissions could be reduced by up to 47%. On the other hand, consumption-based CO_2 emissions could be reduced by up to 32%.[16]

Figure 8 breaks down the potential reduction in CO_2 emissions by state.[17] The largest decrease in production-based CO_2 emissions would occur, in absolute terms, in Minas Gerais (25,947 thousand tons) and in relative terms, in Espírito Santo (71%). The reductions would be concentrated in the "basic metals and fabricated metal" sector of these states (also in the "transport" sector in Minas Gerais), which show considerably larger CO_2 coefficients than the coefficients for São Paulo's adopted in the simulation. The differential in the CO_2 coefficient for the "basic metals and fabricated metal" sector also accounts for a substantial share of the potential reduction in Rio de Janeiro's production-based emissions. In Bahia, it is the differential in the "chemicals and chemical products" sector's CO_2 coefficient that mostly accounts for the potential reduction.

Reflecting its privileged ownership of relatively clean technologies in 2008, São Paulo is the only state in our simulation with a potential reduction of consumption-based emissions greater than that of production-based emissions. Under a technology transfer mechanism, São Paulo's consumption-based CO_2 emissions could be reduced by up to 20,332 thousand tons (22%).

[16] The potential reduction of consumption-based CO2 emissions is lower than that of production-based emissions because we do not modify the CO2 coefficients in foreign countries in our simulation, and part of the now less carbon-intensive production is exported.

[17] In this exercise, the carbon intensities analyzed in subsection 4.3.4 are modified but are still distinct for each state. The intensity of production-based CO2 emissions vary because of the composition of production baskets and the different gross output/value-added ratios in the states' industries. Concerning the per capita consumption-based CO2 emissions, given the various composition of consumption baskets and different levels of final demand expenditure per capita, they still vary across states.

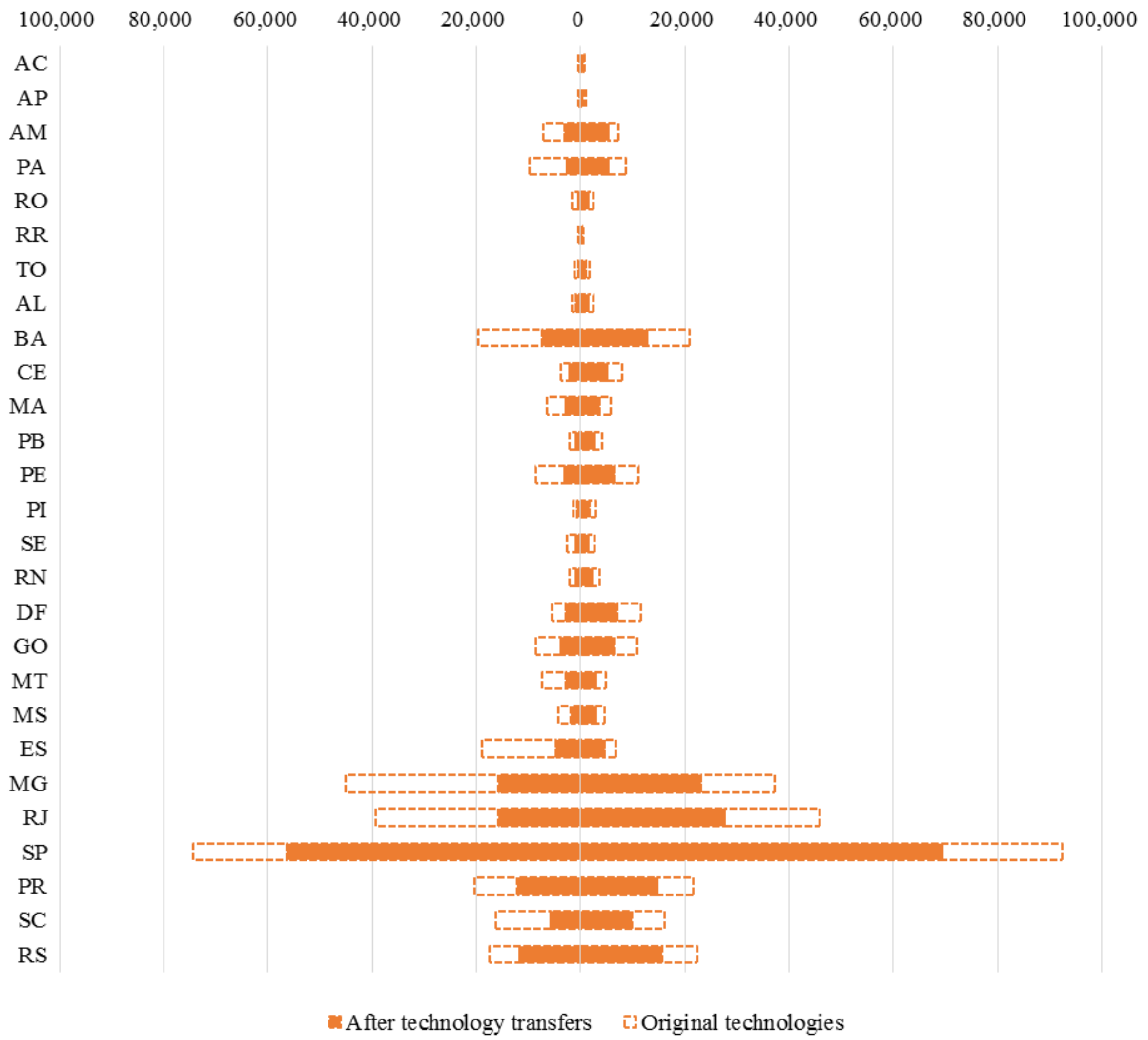

Figure 8 – Results of the simulation: potential reduction in production-based and consumption-based CO_2 emissions (in thousand tons)

4. Concluding remarks

The fragmentation of production processes has caused profound changes in the spatial organization of economic activity. We observed the dispersal of production at the global level, as more countries can join the fragmented value chains. On the other hand, at the regional level, exploiting economies of scale leads to greater specialization in productive activities, especially intra-establishments, as indicated by Hewings and Oosterhaven (2015). In environmental terms, the consequence is a greater spatial concentration of harmful activities in specialized regions. This is important from the perspective of climate change policies, as binding emission mitigation targets might affect the activity levels within these regions to a larger extent. In this sense, policymakers face the challenge to ensure that regions specializing in pollution-intensive activities adopt clean technologies, as suggested by Peters and Hertwich (2008), rather than further slicing up the value chain and moving the polluting fragments outside the policy's control (i.e. by leaking avoidable carbon) or not participating in climate change regime.

The current framework of climate policies in Brazil suggests that carbon leakage is not regulated within the country – while national policies neglect the regional distributive implications from mitigation efforts, state participation in mitigation commitments via subnational initiatives is limited. On the other hand, since most of the polluting activities, such as mining and metallurgy plants, cannot be easily relocated, given that only certain states are naturally endowed with these resources, it is not expected that the current sub-national policies elaborated at spontaneous and autonomous grounds lead to thorough mitigation efforts.

In this chapter, we consider that it is important to understand the relationship between trade and emissions in order to devise effective climate policies. With this in mind, our objective was to trace the CO_2 emissions embodied in Brazilian states' trade, both within the country and internationally. Recognizing the interconnectedness of domestic and global value chains, we applied a country–state IO table for the year 2008, which explicitly displays the Brazilian states' economic interrelationships and their relationships with foreign countries. To extend the model environmentally, we compiled a novel database reflecting CO_2 emissions from energy use (i.e. fossil fuel combustion) by state and production industry.

A central finding of our analysis is that not only were 28% of global emissions (from fossil fuel combustion) embodied in international trade, but 36% of territorial emissions (from fossil fuel combustion) in Brazil were traded between states. Thus, international and interregional trade play a major role in emissions reduction and should be given due consideration in the climate change policy framework. The current regional mitigation initiatives in Brazil, which are limited to a few states and refer only to the emissions generated within states' territorial boundaries, ignore an important share of national emissions.

Our observation that consumption-based CO_2 emissions intensities do not decrease as states become wealthier points out the necessity of proactive climate policies. In this regard, our study's quantification of consumption-based emissions produces an alternative indicator to the territorial principle that guides the mitigation commitments at both the federal and state levels in Brazil. However, arguably, this solution takes the problem from one extreme to another, that is, shifting the burden of mitigation entirely from producers (who benefit from economic activity in their respective territories) to final consumers. For an intermediate solution, as Peters (2008) indicated for the global level, consumption-based indicators within countries may help establish different commitments that are trade-adjusted, adhering to the principle of "common but differentiated responsibilities" at the regional level. In addition, consumption-based indicators can be used to identify priority mitigation activities under some CDM. In fact, we recognised that transfers of climate-friendly technologies within Brazil offer great potential as a mitigation policy tool. Considering the technologies available within the country in 2008, production-based emissions from energy use could be reduced by up to 47%. The analysis of states' international TiCE can also help prioritize developed foreign countries' CDM initiatives hosted by Brazilian states.

Such potential is possible because of considerable heterogeneities in CO_2 emissions across Brazilian states. In this paper, we not only observed very different carbon quantities in the interregional and international trade flows but also identified huge variations in production-based emission intensities. Similar to our verification for the TiVA flows, we also found that production- and consumption-based emissions are largely concentrated in the more developed Southeast and South regions of Brazil. However, there are important differences in the participation of the states within these regions. Particularly, São Paulo's is less dominant with regard to TiCE, while Espírito Santo and Minas Gerais emerge as main sources of TiCE on account of their mining and metallurgical activities. Unlike the case of China (FENG *et al*, 2013; PEI *et al*, 2015), we do not observe a clear pattern of coastal and rich regions being recipients of net emissions transfers from inland states for the case of Brazil. Given our verification of dissimilarities across neighbouring states, it is vital that subnational climate policies contemplate each case.

Our results refer to CO_2 emissions from fossil fuels combustion in the year 2008. Since then, the share corresponding to energy use in Brazil's GHG emissions has soared (LUCON *et al*, 2015). Thus, we consider that our findings might be amplified with data for more recent years. In this context, it is worrisome that the current mitigation strategy of the federal government for this sector is largely limited to keeping the national energy matrix relatively clean via use of hydroelectricity and biofuels. It therefore appears that an important trade-off has not been adequately weighed: as indicated by Hoekstra and Wiedmann (2014), even though these two energy sources reduce carbon emissions, they inevitably increase land and water footprints. For instance, it is remarkable that ethanol production for use within the state of São Paulo alone accounted for 17.5% of total water consumed in the state in 2009 (VISENTIN *et al*, 2015). The severe water crisis that started in 2010 makes it even more pressing to look for energy alternatives. Otherwise, as Abramovay (2010) states, the advantage of having a clean energy matrix may instead become a curse.

We have reiterated throughout this chapter the need for coordination of top-down policies in addressing climate change. Interregional carbon leakage has to be taken into consideration for achieving a nation-wide goal of mitigation, and thus, coordination among the interlinked economies is fundamental. As a matter of fact, devising a central arrangement is easier within countries than at the global level, as the federal government can design policies covering the subnational regions. However, this does not preclude subnational climate initiatives, especially when it is fundamental to encourage new alternatives in the energy sector, as regional policies can recognize spatial particularities and are especially prone to innovations. In this regard, our identification of the most important flows in interregional trade in emissions can provide a solid ground for environmental alliances between states. In doing so, the vertical and horizontal coordination of Brazilian subnational climate policies is likely to increase the chances of more effective implementation.

5. References

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Annex

Table A1 – Inter-regional trade in CO2 emissions (in thousand tons)

	AC	AP	AM	PA	RO	RR	TO	AL	BA	CE	MA	PB	PE	PI	SE	RN	DF	GO	MT	MS	ES	MG	RJ	SP	PR	SC	RS	Total
AC	-	0	2	4	2	0	1	1	7	3	2	4	5	1	1	2	7	3	2	2	3	12	14	30	7	6	12	135
AP	0	-	1	2	0	0	0	0	4	2	1	1	2	0	1	1	4	2	1	1	2	8	8	17	4	3	7	72
AM	12	13	-	136	46	9	20	28	172	84	60	47	116	38	33	44	161	97	72	42	91	352	532	1,509	171	134	221	4,238
PA	5	6	34	-	14	3	11	16	86	51	60	26	58	23	13	30	119	45	26	25	44	165	242	486	105	86	176	1,956
RO	6	2	36	17	-	1	2	5	31	13	15	8	17	6	5	7	53	14	10	11	22	63	76	161	42	22	69	713
RR	0	0	1	3	1	-	0	0	5	2	1	1	2	1	0	1	3	2	1	1	1	7	23	15	3	4	5	83
TO	1	2	7	23	3	1	-	3	24	16	21	7	14	7	4	5	31	18	5	6	11	57	51	95	18	14	36	479
AL	1	2	6	16	6	1	3	-	52	19	6	16	62	8	11	7	16	10	6	5	7	38	112	95	22	21	28	576
BA	18	20	85	177	54	10	37	80	-	189	107	102	285	77	103	98	272	166	100	86	165	588	692	1,778	323	293	389	6,296
CE	3	5	16	45	8	2	5	10	78	-	32	38	70	49	9	70	33	30	11	10	17	79	95	213	38	48	54	1,069
MA	12	9	35	176	29	6	39	26	200	85	-	39	85	83	16	43	108	88	60	23	40	365	244	480	103	80	138	2,613
PB	5	2	9	20	5	1	3	15	57	61	15	-	71	10	9	61	41	12	7	9	16	58	68	162	24	30	48	820
PE	7	9	40	82	21	5	14	82	372	206	76	213	-	50	45	98	158	56	34	37	71	221	289	662	117	93	216	3,274
PI	1	2	5	16	3	1	3	3	22	33	45	5	12	-	2	4	12	8	4	4	6	26	36	75	17	14	25	383
SE	3	4	16	27	10	2	6	23	142	36	24	15	42	14	-	16	87	37	14	17	31	108	145	309	55	45	118	1,344
RN	2	3	14	24	7	1	4	6	67	50	12	22	34	10	8	-	31	20	12	9	17	79	64	234	48	36	59	873
DF	4	7	15	44	18	2	13	7	80	25	12	21	25	17	6	14	-	127	11	12	18	209	387	205	34	39	51	1,402
GO	9	11	38	110	22	5	39	23	145	75	49	45	85	33	22	48	169	-	50	35	49	384	303	729	166	97	139	2,879
MT	10	15	60	134	50	5	16	26	204	86	62	60	95	46	27	41	98	74	-	64	55	280	598	672	258	131	171	3,337
MS	6	7	43	68	17	3	9	14	102	41	30	26	45	21	14	20	53	45	43	-	28	147	256	530	142	87	88	1,886
ES	18	18	117	185	52	10	36	55	440	155	101	83	222	59	57	82	248	219	115	82	-	817	1,013	2,543	429	272	395	7,826
MG	40	44	227	401	112	24	82	116	843	460	230	176	438	127	122	164	555	587	226	175	552	-	2,237	4,565	778	538	764	14,585
RJ	42	42	210	464	124	25	84	116	717	338	226	177	449	136	121	181	572	448	244	171	504	1,444	-	3,665	692	691	837	12,718
SP	95	117	499	1,082	310	54	183	262	1,932	769	440	435	971	334	232	403	1,320	1,032	548	432	630	3,702	5,535	-	1,807	1,317	2,141	26,581
PR	37	37	105	402	96	19	68	76	527	178	125	123	212	97	60	113	338	268	191	122	140	1,006	1,225	2,309	-	529	582	8,986
SC	24	26	98	271	63	13	45	63	387	172	136	90	196	74	58	86	295	183	106	99	150	683	835	1,675	716	-	721	7,265
RS	24	25	79	266	72	11	48	56	354	183	138	102	183	88	53	87	229	187	103	71	125	604	992	1,421	345	366	-	6,212
Total	384	430	1,800	4,194	1,145	212	769	1,114	7,050	3,330	2,027	1,884	3,794	1,410	1,034	1,726	5,012	3,778	2,005	1,550	2,796	11,500	16,075	24,635	6,463	4,995	7,490	118,602

Table A2 – Exports in CO2 emissions (in thousand tons), Brazilian states

	CHN	IND	RUS	USA	MEX	CAN	DEU	ESP	FRA	GBR	ITA	Other EU27	JPN	KOR	TWN	Other + RoW	Total
AC	3	0	1	3	0	0	2	1	1	2	1	3	1	0	0	12	31
AP	12	1	1	44	2	3	4	1	2	3	2	8	3	1	1	32	123
AM	56	8	14	137	28	16	52	15	24	24	23	74	20	8	4	362	864
PA	543	60	57	1,249	110	289	270	93	188	102	126	410	442	86	27	1,272	5,325
RO	14	1	23	21	2	3	11	6	6	11	8	21	6	2	1	86	224
RR	1	0	0	2	0	0	1	0	1	1	1	2	1	0	0	6	16
TO	25	1	6	12	1	2	7	12	5	4	3	15	4	1	0	44	142
AL	12	4	10	33	3	7	13	4	7	6	5	26	4	3	1	83	219
BA	406	50	66	911	168	89	422	101	166	137	220	537	134	48	25	1,465	4,946
CE	17	3	7	56	7	7	27	8	13	15	15	43	7	2	1	88	317
MA	208	26	27	460	58	48	90	57	56	44	48	165	75	24	10	633	2,030
PB	9	1	3	30	3	3	8	3	4	4	5	13	4	2	1	44	137
PE	54	9	16	150	19	20	50	17	25	30	24	83	21	8	4	328	857
PI	12	1	2	13	2	2	7	3	5	4	3	10	5	1	1	34	105
SE	21	3	5	51	6	5	16	6	8	8	8	36	8	3	1	125	308
RN	14	2	4	61	4	5	15	9	9	12	8	34	6	2	1	93	278
DF	14	1	5	24	3	3	19	4	7	8	9	29	9	2	1	67	205
GO	159	34	49	134	19	18	105	87	58	48	42	163	53	18	5	454	1,444
MT	375	14	52	168	13	23	107	107	80	79	71	254	59	39	10	745	2,197
MS	94	7	28	139	9	13	43	13	31	22	22	72	28	13	3	314	852
ES	722	93	114	2,484	279	176	393	192	217	164	231	590	436	383	138	2,630	9,241
MG	1,178	159	207	2,799	359	272	936	245	407	333	427	1,196	634	365	214	4,380	14,110
RJ	893	98	101	1,132	181	122	364	156	212	179	200	619	198	86	41	3,009	7,590
SP	847	118	257	2,157	330	244	830	249	404	349	365	1,255	336	137	70	5,261	13,209
PR	332	29	74	428	60	64	280	71	132	98	106	366	115	48	15	1,367	3,586
SC	185	25	60	425	62	58	175	53	85	90	80	263	127	31	12	1,225	2,957
RS	298	30	85	603	69	48	202	58	96	86	89	313	97	38	14	1,441	3,567
Total	6,502	778	1,274	13,725	1,798	1,542	4,448	1,569	2,249	1,862	2,143	6,601	2,834	1,353	601	25,600	74,880

Table A3 – Imports in CO2 emissions (in thousand tons), Brazilian states

	AC	AP	AM	PA	RO	RR	TO	AL	BA	CE	MA	PB	PE	PI	SE	RN	DF	GO	MT	MS	ES	MG	RJ	SP	PR	SC	RS	Total
CHN	33	69	1,976	499	187	19	117	138	1,341	544	263	356	610	197	130	184	544	625	230	341	769	2,579	2,589	10,044	2,226	1,718	1,499	29,829
IND	4	5	55	51	19	2	12	14	145	203	127	31	69	20	21	26	103	87	31	44	58	277	305	955	223	183	209	3,279
RUS	9	11	95	113	29	5	21	28	331	96	182	52	152	34	33	41	144	162	68	66	89	539	531	1,500	385	220	441	5,378
USA	15	20	193	249	48	9	35	51	405	158	163	81	262	53	62	76	264	242	91	102	165	792	1,159	3,043	534	352	519	9,141
MEX	1	1	24	10	3	1	2	2	40	9	7	5	26	3	3	4	15	11	5	5	13	53	55	208	62	25	37	630
CAN	6	7	44	62	17	3	12	19	129	58	41	29	86	20	17	25	89	114	42	39	54	363	304	777	215	105	184	2,861
DEU	9	10	77	88	27	6	18	19	160	77	48	35	107	24	25	33	115	88	34	53	61	348	463	1,209	240	147	215	3,737
ESP	1	1	10	13	4	1	5	3	58	16	8	6	17	4	4	5	19	15	7	8	13	56	94	229	54	32	44	726
FRA	1	2	13	15	4	1	3	4	30	13	9	6	20	4	4	5	28	18	7	9	15	71	119	269	65	30	44	809
GBR	2	2	21	21	6	1	4	5	55	21	25	10	37	7	6	9	42	26	10	15	19	94	177	380	76	45	68	1,184
ITA	2	2	18	22	6	1	5	6	49	20	12	10	25	7	6	9	35	26	10	14	23	156	141	394	81	51	78	1,206
Other EU27	9	11	91	101	28	5	19	24	201	87	71	41	123	28	27	37	141	111	47	65	76	402	551	1,434	325	190	282	4,528
JPN	3	4	118	41	10	2	7	10	94	35	23	18	43	11	11	15	47	85	20	20	49	201	222	791	145	89	128	2,243
KOR	2	3	128	33	9	1	6	9	90	30	29	16	41	9	9	13	41	189	17	19	70	156	192	674	127	90	112	2,116
TWN	2	3	87	30	10	1	6	8	76	30	40	16	33	9	8	11	36	36	15	17	40	148	154	639	123	82	96	1,757
Other + RoW	60	74	630	764	203	36	146	183	2,290	696	770	363	1,174	227	215	283	1,005	951	410	485	617	3,065	3,778	10,709	2,426	1,758	3,239	36,558
Total	160	226	3,580	2,111	611	95	419	521	5,493	2,093	1,819	1,074	2,827	656	579	777	2,669	2,786	1,043	1,302	2,134	9,301	10,833	33,255	7,308	5,116	7,194	105,982