Do the metrics matter? Region-specific carbon footprints of Brazilian products

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Abstract

Sustainability in production and consumption can be assessed as long as environmental information is available, which requires appropriate measurements and indicators. This study quantifies the region-specific carbon footprints of Brazilian products. Its novelty is to consider different sources of emissions, which is obtained from a detailed database of Brazilian emissions that enables a distinction between legal and illegal areas. The emissions intensity of products is estimated using a Multi-Regional Input-Output (MRIO). Results show that the metrics matter when quantifying the carbon footprints of products in Brazil, particularly those food-related given the large economic and environmental heterogeneity across regions. This reflects the particularities of each state in terms of productive structure as well as emissions profile. The findings highlight the importance of considering region-specific carbon footprints rather than compiled databases in order to avoid misleading policy decisions aimed at promoting sustainability.

1 Introduction

Sustainable development has become a global commitment to ensure the continuity of future generations while allowing countries to develop without exceeding safe boundaries. Achieving sustainable production and consumption patterns involves adopting strategies to minimise environmental and social costs. From the production side, it implies decoupling economic growth from environmental degradation, increasing the efficiency of natural resources use. With regard to consumption, it is related to the process of purchasing, consuming, and disposing of products, including lifestyle changes to limit over-use. However, production and consumption sustainability can be assessed as long as environmental information is available, requiring better measurements and indicators [3].

This analysis represents a significant advancement in the quantification of carbon footprints in Brazil. By using an environmental extended input-output approach and incorporating detailed emission data, it links environmental issues with production and consumption. Unlike previous studies, this research provides country-specific carbon footprint information for each Brazilian state, accounting for emissions from all sources including agriculture, land use, energy use, industrial process, and waste. More specifically, it distinguishes emissions associated with legal and illegal land use.

Most studies to date are limited to energy-based emissions [10] or used life cycle databases [5] that may not be nationally representative, and disregard emissions from land use [2] and deforestation [4], resulting in underestimated carbon footprints. Including these emissions in the carbon footprint of Brazilian products is highly relevant given that they represent a large share of total national emissions but also because disregarding them may undermine efforts to meet the climate commitments.

To fill this gap, we adopted an empirical approach based on an estimated Multi-Regional Input-Output (MRIO) matrix for 2015 and emissions data from Mapbiomas [8] and SEEG [1] to develop a comprehensive understanding of the carbon intensity of 128 products across Brazilian states. Calculating the carbon intensity coefficient (tonnes of CO2e/US$ million) required to create a correspondence between emissions sources and the MRIO products. Mapbiomas database captures the loss of natural area (in pixels) converted into carbon biomass while SEEG details emissions of other sources at disaggregated levels and for several Greenhouse Gases (GHGs).

The findings highlight the importance of considering region-specific carbon footprints rather than compiled databases in order to avoid misleading policy decisions aimed at promoting sustainability. In this sense, it can support future investigations on sustainability from both the production and consumption perspectives. Its contribution to the scientific literature is methodological since it incorporates emissions from the major sources into the estimation, but also empirical by providing evidence of carbon footprints at the product and regional levels.

The paper is organised as follows. Section 2 describes the empirical strategy as well as the data used in the estimations. Section 3 presents the nationwide and regional carbon footprints of Brazilian products. Section 4 brings some concluding remarks and further indicates the next stages of the research.

2 Empirical strategy and data

3 Estimating carbon intensity coefficients

The analysis of this paper is based on results obtained after combining the MRIO matrix and emissions data. By doing so, it provides a comprehensive understanding of the carbon intensity of 128 products across Brazilian states. This section details the procedures to create the database containing economic and emissions information and the subsequent stages to calculate the carbon footprints, as summarised in 1

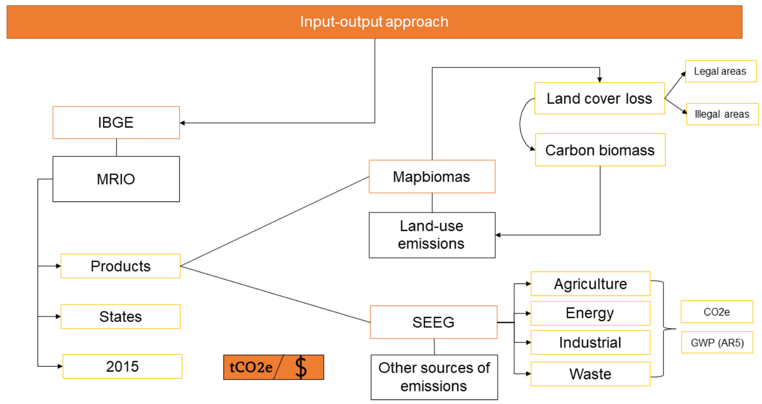

Figure 1: General overview

3.1 Input-Output approach

As a "top to bottom" method, the input-output approach has become a globally applicable and relevant carbon footprint assessment tool [6] to track the emissions embodied in economic activities. It represents interdependencies between industrial sectors within an economy. Mathematically, it is traditionally written as:

$$\sum_{j=1}^{n} z_{ij} + y_i = \sum_{j=1}^{n} a_{ij}x_j + y_i, \forall i, j = 1, ..., n \ (1)$$

where z_{ij} represents the value of purchases of industry i output by industry j ($z_{ij} \in \mathbf{Z}$); y_i is industry i sales to final demand ($y_i \in \mathbf{Y}$); x_i is industry i gross output ($x_i \in \mathbf{X}$); and $a_{ij} = z_{ij}/x_j$ represents the technical coefficients ($a_{ij} \in \mathbf{A}$). Following Miller and Blair's specification [9], the so-called Leontief inverse matrix $\mathbf{L}$ ($l_{ij} \in \mathbf{L}$) is described as:

$$\text{X=(I-A)}^{-1}Y = LY \ (2)$$

where $\mathbf{I}$ is an identity matrix.

This version of the input-output table is obtained by combining it with other tables. There is $\mathbf{U}$ ($u_{ij} \in \mathbf{U}$), a matrix with demand values for commodity i by industry j, and $\mathbf{B} = \mathbf{U}\widehat{\mathbf{X}}^{-1}$ ($b_{ij} \in \mathbf{B}$), where $\widehat{\mathbf{X}}$ is a diagonal matrix of $\mathbf{X}$. Further definitions include $\mathbf{Q} = \mathbf{Ui} + \mathbf{F}$, where $\mathbf{Q}$ represents the total commodity output; $\mathbf{F}$ is commodity final demand and $\mathbf{i}$ represents a column vector of ones. Then, $\mathbf{Q} = \mathbf{BX} + \mathbf{F}$. Other elements are depicted in $\mathbf{D} = [d_{ij}] = \mathbf{V}\widehat{\mathbf{Q}}^{\mathbf{-1}}$, where $\mathbf{V} = [v_{ij}]$ is the MAKE matrix that contains the elements v_{ij} with values of the output of commodity j that is produced by industry i; $\widehat{\mathbf{Q}}$ is the diagonal matrix $\mathbf{Q}$; and $\mathbf{D}$ is the market shares matrix and d_{ij} denotes the fraction of total commodity j output that industry i produced. Finally, we can express $\mathbf{X} = (\mathbf{I} - \mathbf{DB})^{\mathbf{-1}}\mathbf{Y}$, where $\mathbf{DB}$ is equivalent to matrix $\mathbf{A}$ and $\mathbf{DU}$ is equivalent to $\mathbf{Z}$. The above conceptual description for a single region can be applied to a multi-regional case. For more details see [9].

3.2 Obtaining the MRIO matrix

In the first stage, we estimated the MRIO for the Brazilian regions. We obtained the most recent version of the Brazilian input-output matrix from the Brazilian Institute of Geography and Statistics (IBGE)[7] for the year 2015. The matrix contains information on monetary flows across 68 sectors. We also obtained the corresponding MAKE matrix, which contains information on 128 products [1] and 68 sectors. To regionalize the nationwide input-output matrix, we used a detailed MRIO for the 27 Brazilian states (regions) from 2011 [**?**]. Assuming that the production technology in each state (and between them) remained unchanged between 2011 and 2015, we multiplied the MAKE and the regional blocks of the MRIO matrix to obtain a Brazilian MRIO for 2015. The MRIO specifies the products, sectors, and regions, enabling us to identify the type of product each sector demands, including its regional information of origin and destination.

3.3 Reconciling Emissions Sources with the MRIO Products

In this step, we reconcile all emission sources (agriculture, land use, energy use, industrial process, and waste) with the MRIO products. Two different approaches are adopted for land use emissions and other emissions. This is explained in the following subsections.

3.3.1 Emission data: Land use change

To calculate carbon emissions from land use, we use data from Mapbiomas[2] platform, which provides land cover and land use data in Brazil [8]. Each pixel has a resolution of 30 m2.

For this analysis, we collected land use cover data for Brazil from 2014 and 2015 (collection 7 of the dataset), to match with the year of the MRIO. This

[1] The complete list of products with information available at the input-output matrix is provided in Appendix **??**.

[2] MapBiomas is a multi-institutional initiative, which involves universities, NGOs and technology firms, dedicated to understanding the changes of the Brazilian territory using annual mapping of land cover and land use in Brazil.

land use data have been reclassified to correspond to the products listed in the MRIO, resulting in 15 land use categories. The land use categories are: ID1 – Natural areas (MapBiomas classes: 3-5-11-12-13-29-32-49-50); ID2 – Soybean (39); ID3–Sugar cane (20); ID4 – Rice (40); ID5 – Cotton (62); ID6 – Other temporary crops (41); ID7 – Citrus (47); ID8 – Coffee (46); ID9 – Other perennial crops (48); ID10 – Pasture (15); ID11 – Forest plantation (9); ID12 – Mining (30); ID13 – Aquaculture (31); ID14 – Water (33); ID15 - Other non-vegetated areas (21-23-24-25-27). A novelty of this study is to distinguish between land-use change in legal and illegal areas. To do so, we identified economic activities occurring in Conservation Units and indigenous areas, classifying them as illegal.

The reclassified land use maps were divided into 27 Brazilian states (regions), and land use changes were supervised by the Semi-Automatic Classification Plugin (SCP) for QGIS [?]. Figure 2 shows an example of land cover change analysis done with SCP. We selected an area in the interior of Pará, Brazil (8°N, 8°E). Figure 2 (top, mid) shows land use maps for 2014 and 2015, respectively. Figure 2 (bottom) shows the land use change map focusing on the transition from natural areas to other land cover classes. In this study site, it is observed, for example, pixels that were natural areas in 2014 and converted to pasture, soybean, other temporary crops, and mining in 2015. This allowed valuing the losses of natural areas and the economic sources (anthropogenic) responsible for the change. It is worth noting that corn crop is not explicitly detailed in the MapBiomas data, but is included in 'Other temporary crops'. Hence, we used information on the cultivation area from the Municipal Agricultural Production Survey (provided by the IBGE) to attribute land-use emissions to the corn crop.

We converted natural area losses into carbon biomass using data from the global map of aboveground and belowground biomass carbon density for the year 2010 [?] and released by the Distributed Active Archive Center for Biogeochemical Dynamics (ORNL DAAC). These data allow a breakdown of the carbon biomass by region. This is particularly useful for Brazilian reality because of the heterogeneity of the vegetation cover of Brazilian biomes.

3.3.2 Emission data: Other sources

For the other emission sources (agriculture, energy use, industrial processes and waste), we used data from the SEEG (System for Estimation of Emissions and Removal of Greenhouse Gases) platform. They provide complete information on Brazilian emissions at the national, state and municipality levels. To match with the year of the MRIO, we collected emissions data from collection 8 for 2015 by state. The SEEG database classifies emissions into three categories: emissions, removal [3] and bunker (for international maritime and air transport). For this study, the SEEG data includes carbon, methane, nitrous oxide and hydrofluorocarbons expressed in carbon equivalent emissions (CO2e) determined in terms of the Global Warming Potential (GWP) and according to the conversion factors of the fifth IPCC report (AR5). This version is also used in the

[3] It includes removals from protected areas, which is outside the scope of the analysis whose focus is on the transition from economic to natural use.

Brazilian National Determined Commitment (NDC). Even though SEEG has incorporated Mapbiomas data into the collection 8 database, we opted to collect land use change data directly from Mapbiomas to facilitate the correspondence with the MRIO products. SEEG does not allow identifying the linkage between products and land use in detail, which is essential for a comprehensive and accurate estimation using the input-output approach. A picture of the emissions profile by each state found in the SEEG database is provided in Figure 3.

As previously mentioned, emissions data have been reclassified to create a correspondence between the different levels of information associated with each of the sectors emitting and the products listed in the MRIO. By concatenating the information, 632 categories were created and subsequently reclassified. To do so, we separated the categories with direct correspondence with a certain product of the MRIO from those associated with several products, as described in the dictionary created. In this process, the scientific literature was used as a guide to help classify some sectors. Residential emissions were excluded.

We adopted a different approach for the categories with multiple correspondences, corresponding to 33% of the database. In these cases, we created groups and calculated the share of each product in that specific group based on the Gross Production Value (GPV) of the group in each state. This resulted in 17 groups with different shares. The use of GPV shares is based on the assumption that the largest the GPV of a product, the more emissions its production generates.

We first calculated the direct emissions of each product by state. For multiple correspondence categories, we use the shares of step 3 to attribute emissions to products of the MRIO. We disregard emissions not allocated for any state, representing 6.5% of the total database in 2015. The total emissions per product by state correspond to the sum of values from the two approaches. To facilitate tracking the drivers of emissions in each state, we also distinguished emissions by product and state and sectoral source of emission (agriculture, energy use, industrial process and waste).

3.4 Use of MRIO and emissions to calculate carbon intensity coefficients

To calculate the carbon intensity, we first developed a matrix $\boldsymbol{E_s}$ that represented the territorial emissions of economic activities by source (agriculture, land use, energy use, industrial process, and waste). This matrix was based on emissions data from Mapbiomas and SEEG.

The technical coefficient matrix $\boldsymbol{A}$ by product and Brazilian state was then used with the matrix $\boldsymbol{E}$ to generate the final emissions by product. The final emissions were calculated by emissions source s, allowing for a comprehensive understanding of the carbon intensity of each product in each state:

$$\boldsymbol{E_s^*} = (I - \boldsymbol{A}) \times \boldsymbol{E_s} \tag{3}$$

where $\boldsymbol{E^*}$ is a matrix with the elements of $\boldsymbol{E_s^*}$ on final emissions coefficients.

The matrix comprises coefficients by product i and Brazilian state r.

The coefficients can be interpreted as the quantity of CO_2e that a product i from region r uses to produce one unit of product j (expressed in ton CO_2e/USD, in 2015 values. To express the monetary values in US dollars, we used the nominal exchange rate in 2015 from the Brazilian Central Bank. The emissions intensity of the Brazilian products is calculated using the GPV values of the MRIO and the emissions data detailed in the previous section. The intensity coefficient translates the total CO2e emissions, in tonnes, for each US$ million produced.

4 Results: region-specific carbon footprints

This section presents the region-specific carbon footprints of Brazilian products. This is a preliminary version of the emission intensity coefficient, which is yet to be adjusted [4]. Figure 4 shows the emissions profile of Brazil in terms of carbon intensity, indicating that the total emissions intensity of agriculture and livestock products is considerably higher than those of other sectors. This is largely due to enteric fermentation and animal waste management. Considering the Brazilian carbon footprint, agriculture and livestock are responsible for 41% of the nationwide emissions intensity, followed by land use change (23%). The use of Mapbiomas data enabled the identification of emissions associated with land uses in illegal areas, representing 8% of the total land use carbon footprint. Other sources of emissions (energy use, industrial processes and waste) respond altogether for 36% of the Brazilian carbon footprint.

Figure 5 differentiates the carbon footprint by MRIO product but disregards emissions related to illegal land uses. Animal husbandry, bovines in particular, ranks first while milk products rank second with regard to emissions intensity in Brazil. However, Figure 6 demonstrates the emissions intensity and its drivers vary across states. For example, cattle production in Pará and Amazonas involves more land use change emissions than emissions from agriculture, which is the opposite of what occurs in the middle-east state of Mato Grosso. In Brazil, cattle and live animals are raised in all states, thereby releasing emissions. Yet, the emissions intensity of legal land use as well as from agriculture is mostly concentrated in the states of the North and those located in the Amazon region. A summary of the land footprint estimated for each Brazilian state is provided in Figure 7.

A novelty of this study is to consider different sources of emissions, also referred to as sectors. Previous studies have assessed carbon footprints using energy use emissions. To illustrate the heterogeneity of the carbon footprint derived from energy use by state, we exhibit Figure 8. Similar to the case of land footprints, the largest energy footprints are concentrated in two regions, they are the Southeastern and South regions. São Paulo is the most populous and wealthiest Brazilian state as it contributes to 32% of the Brazilian Gross

[4] The presentation will consider the final version containing direct and indirect emissions

Domestic Product (GDP). Overall, our findings reveal that mineral coal, transportation and cement have the largest emissions intensity amongst all products, as depicted in Figure 9. There are also those products characterised as services, such as public and private education or healthcare, whose activities do not involve the direct release of emissions. For these MRIO products, associated emissions will be captured in the next methodological stage of this paper and discussed in the final version of the paper.

Waste-related emissions are generally excluded from the accountability of carbon footprints. To address this issue, we estimated in Figure 10 waste footprints for the Brazilian states, for which only eight categories of products generate waste-related emissions. In this type of footprint, Water, sewerage, and drainage services predominate at the national and regional levels. The emissions intensity of the milk industry in relation to waste is also significant. A detailed analysis of the industrial and agricultural sectors will be provided in the final version.

5 Concluding remarks

This paper quantifies the carbon footprint of Brazilian products differentiated by region and source of emissions, separating emissions associated with legal and illegal land use. This is a significant advancement in the quantification of carbon footprints in Brazil since most studies to date are limited to energy-based emissions or used life cycle databases that may not be nationally representative, and disregard emissions from land use and deforestation, resulting in underestimated carbon footprints.

Our evidence shows that the metrics matter when quantifying the carbon footprints of products in Brazil, particularly those food-related given the large economic and environmental heterogeneity across regions. This reflects the particularities of each state in terms of productive structure as well as socio-ecological system and emissions profile. For example, land use represents 50% of the nationwide carbon footprint of cattle and other live animals while in Pará it corresponds to 77% of its total carbon footprint. This is the major emissions-intensive MRIO product in Brazil.

The findings highlight the importance of considering region-specific carbon footprints rather than compiled databases in order to avoid misleading policy decisions aimed at promoting sustainability. We will add to the final version of this paper the indirect emissions and a wider discussion based on the scientific literature. While improved supply-side production techniques have the potential to mitigate the environmental impact of production, there is also significant room for demand-side options, including shifts towards more sustainable and healthier dietary choices. In future studies, we will use this analytical tool to evaluate the effects of implementing mitigation policies across the Brazilian states.

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A List of the input-output products

	Product
1	Rice, wheat and other cereals
2	Corn
3	Herbaceous cotton, other temporary crop fibres
4	Sugar cane
5	Soy
6	Other products and services of temporary crop
7	Orange
8	Coffee (beans)
9	Other products of permanent crop
10	Cattle and other live animals, animal products
11	Cow milk and other animal milk
12	Swine
13	Poultry and eggs
14	Forestry products
15	Fisheries and aquaculture
16	Mineral coal
17	Non-metallic minerals
18	Petroleum, natural gas and supporting services
19	Iron ore
20	Non-ferrous metallic minerals
21	Bovine meat and other meat products
22	Swine meat
23	Poultry meat
24	Processed fish
25	Chilled, sterilized and pasteurized milk
26	Other dairy products
27	Sugar
28	Canned fruits, vegetables, other vegetables and fruit juices
29	Vegetable and animal oils and fats
30	Processed coffee
31	Processed rice and rice products
32	Products derived from wheat, cassava or corn
33	Balanced animals feeds
34	Other food products
35	Beverages
36	Tobacco products
37	Processed Textile Yarns and Fibers
38	Fabrics
39	Textile articles of domestic use and other textiles
40	Clothing items and accessories
41	Footwear and leather products

42	Wood products, excluding furniture
43	Cellulose
44	Paper, cardboard, packaging and paper goods
45	Printing services
46	Aviation fuel
47	Gasoalcohol
48	Naphthas for petrochemicals
49	Fuel oil
50	Diesel - biodiesel
51	Other products from oil refining
52	Ethanol and other biofuels
53	Inorganic chemical products
54	Fertilizers
55	Organic chemical products
56	Resins, elastomers and artificial and synthetic fibers
57	Agricultural pesticides and household disinfectants
58	Miscellaneous chemical products
59	Paints, varnishes, enamels and lacquers
60	Perfumes, soaps and hygiene products
61	Pharmaceutical products
62	Rubber products
63	Plastic products
64	Cement
65	Cement, plaster and similar artefacts
66	Glasses, ceramics and other products from non-metallic minerals
67	Pig iron and ferroalloys
68	Semi-finished, flat-rolled, long and steel tubes
69	Metallurgy products of non-ferrous metals
70	Steel and non-ferrous metal castings
71	Metal products, excluding machinery and equipment
72	Electronic components
73	Office machines and computer equipment
74	Electronic material and communications equipment
75	Measuring, test and control, optical and electromedical equipment
76	Electric machines, devices and materials
77	Home appliances
78	Tractors and other farming machines
79	Machines for mining and construction
80	Other machines and mechanical equipment
81	Cars, vans and utility vehicles
82	Trucks and buses, including cabins, bodies and trailers
83	Parts and accessories for motor vehicles
84	Aircraft, vessels and other transport equipment
85	Furniture
86	Products from miscellaneous industries
87	Maintenance and installation of machinery and equipment

88	Electricity, gas and other utilities
89	Water, sewerage, and drainage services
90	Buildings
91	Infrastructure works
92	Construction specialised services
93	Vehicle commerce and repair
94	Wholesale and retail trade, except motor vehicles
95	Land freight transport
96	Land passanger transport
97	Water transport
98	Air transport
99	Storage and auxiliary transport services
100	Courier and other delivery services
101	Accommodation services
102	Food services
103	Books, newspapers and magazines
104	Film, music, radio and television services
105	Telecommunications, cable TV and other related services
106	Development of systems and other information services
107	Financial intermediation, insurance and supplementary pension
108	Effective rent and real estate services
109	Imputed rent
110	Legal, accounting and consulting services
111	Research and Development
112	Architecture and engineering services
113	Advertising and other technical services
114	Non-real estate rentals and intellectual property asset management
115	Condominiums and building services
116	Other administrative services
117	Surveillance, security and investigation services
118	Public administration collective services
119	Pension and social assistance services
120	Public education
121	Private education
122	Public healthcare
123	Private healthcare
124	Arts, culture, sport and recreation services
125	Employer organizations, trade unions and other associative services
126	Computer maintenance, telephone maintenance or appliance maintenance
127	Personal services
128	Domestic services

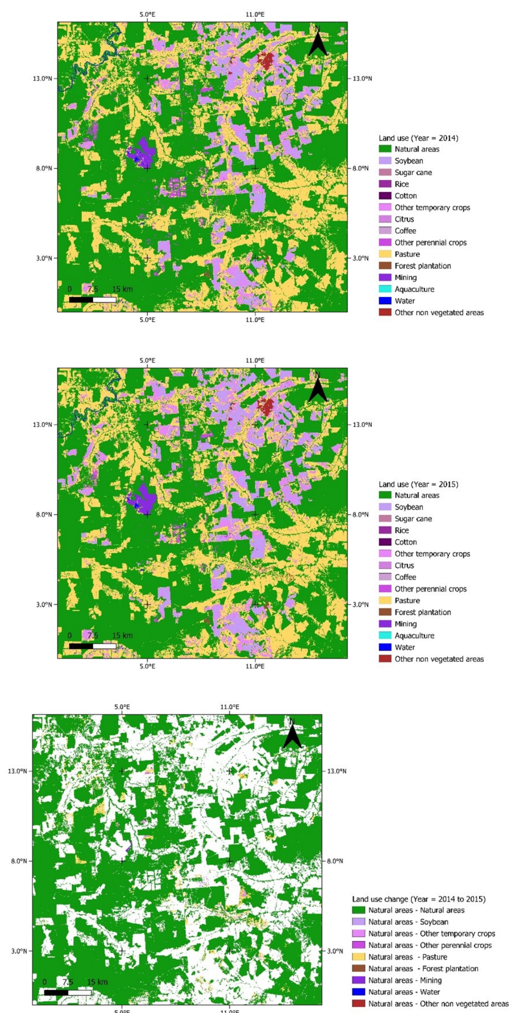

Figure 2: Land use change, 2014 to 2015 (8°N, 8°E)

Figure 3: Emissions profile by state

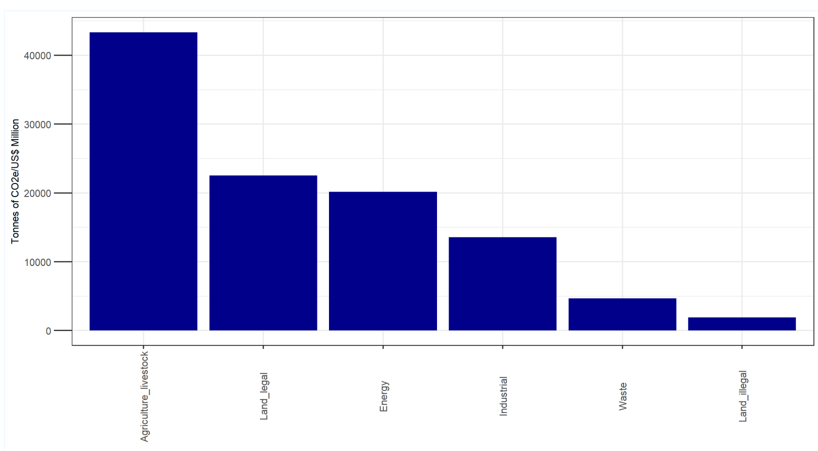

Figure 4: Emissions intensity profile of Brazil

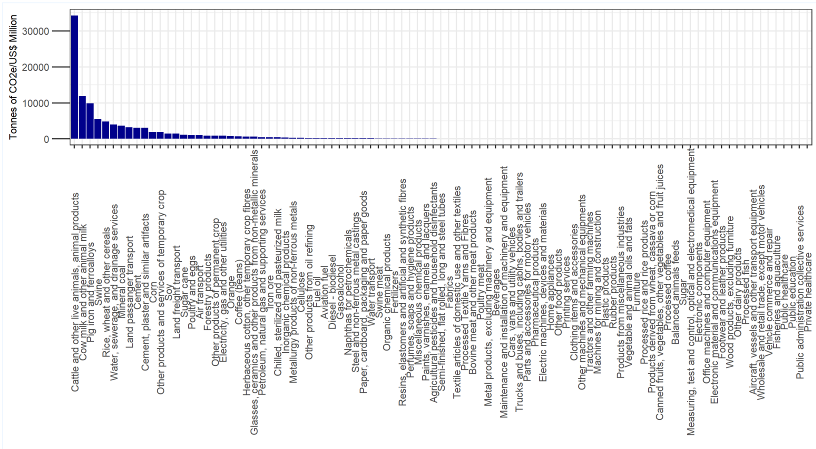

Figure 5: Brazilian carbon footprint (only legal areas considered) by product

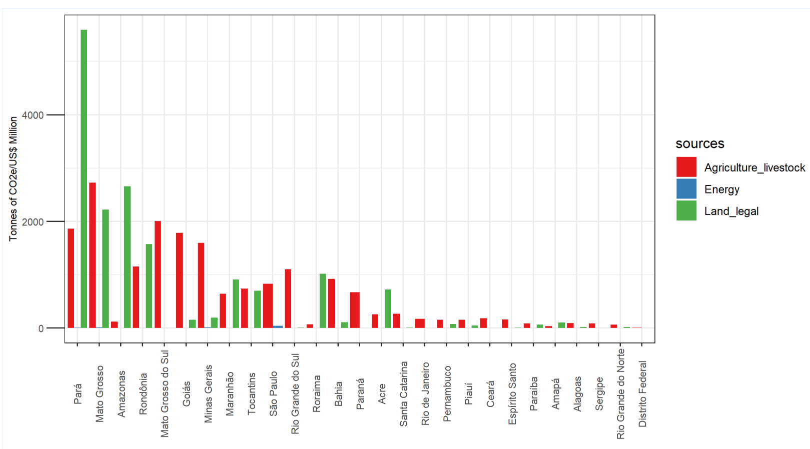

Figure 6: Carbon footprint of cattle and live animals

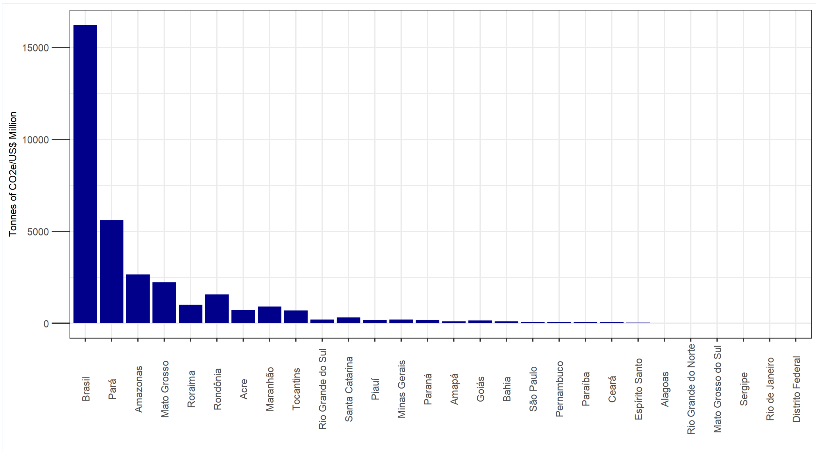

Figure 7: Land use footprint (only legal areas considered) by state

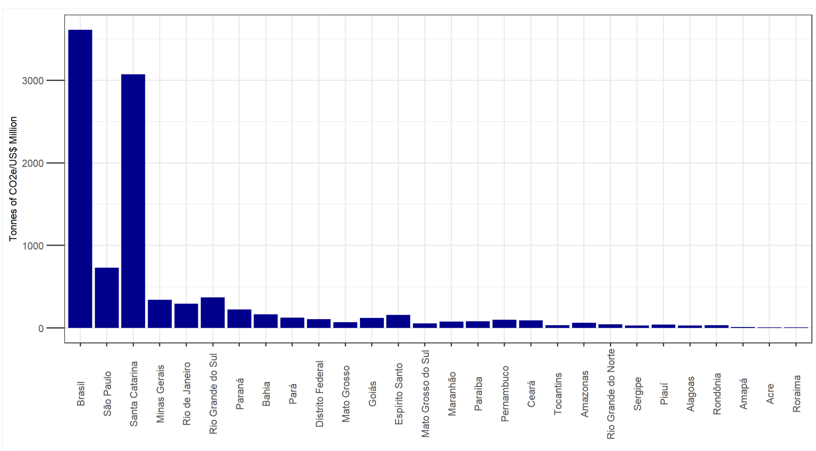

Figure 8: Energy footprint by state

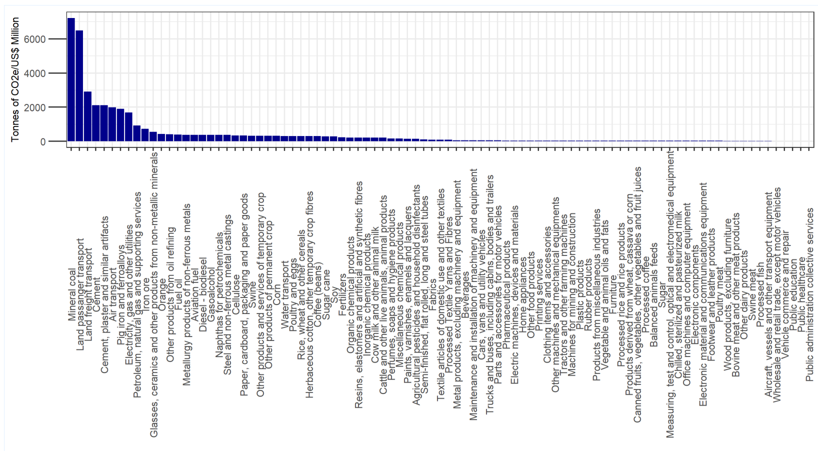

Figure 9: Energy footprint by product

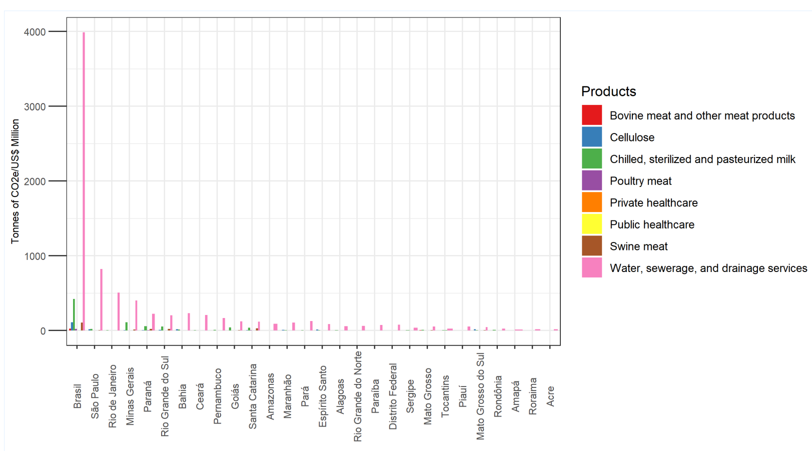

Figure 10: Waste footprint by product